TEMP-84

A COMPUTER MODEL FOR PREDICTING STREAM TEMPERATURES RESULTING FROM THE MANAGEMENT OF STREAMSIDE VEGETATION

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ABSTRACT

TEMP-84 is a computer model developed to simulate temperature responses in small mountain streams that result from shade removal. Stream temperature responses to alternative combinations of cutting unit proposals can be evaluated. Conceptual descriptions of the processes related to the operation of the model, user instructions describing the input data, input data formats, directions for executing the model, and example output are provided. Supporting information about the computational procedures, physical processes, and data sensitivities are also included.

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TEMP-84

A COMPUTER MODEL FOR PREDICTING STREAM TEMPERATURES RESULTING FROM THE MANAGEMENT OF STREAMSIDE VEGETATION

1.0 INTRODUCTION

In forested areas, streams provide important habitat for fish populations. Management of forest cover in streamside zones can influence the quality of this stream habitat by altering energy availability to the stream and hence stream temperatures. Since healthy fish populations depend upon optimal temperatures, potential temperature increases resulting from the loss of shade should be considered during the design and scheduling of forest harvesting operations. Because timber harvesting is scheduled over extended time periods, methods are needed to evaluate the composite effect of several timber harvests along a stream system. The purpose of the TEMP-84 MODEL is to simulate maximum temperature responses for discrete stream sections during periods of low flow and the cumulative downstream temperature response resulting from shade removal at any time over an entire planning horizon. Stream temperature responses to alternative combinations of cutting unit proposals can be evaluated. Such evaluations should provide the land manager with information that will assist in planning (1) the scheduling, and (2) the extent of timber removal along a stream system.

The temperature model requires three general types of information: site characteristics, stream characteristics, and characteristics of the stream-adjacent vegetation. Once these characteristics have been identified for a given stream system, alternative management strategies of the streamside vegetation (clearcut, buffer strips, partial cuts, etc.) can be evaluated to identify potential impacts to stream temperatures. In addition, the effects of regeneration and regrowth of existing cut units along the stream can be accomplished by estimating characteristics of the forest stand at future time periods.

2.0 THE TEMP-84 MODEL - A CONCEPTUAL OVERVIEW

The TEMP-84 MODEL is an expanded version of a temperature simulation model developed by Ponce et al. (1981). This earlier model provided the conceptual framework to which more sophisticated process simulations have been added. Extensive modifications to the energy transfer processes involving solar radiation, longwave radiation, and conductive heat transfer between bedrock and water have been included in the TEMP-84 MODEL. Methods of determining convective heat transfer, evaporative heat transfer, and advected heat in the original model by Ponce et al. (1981) have been incorporated into the TEMP-84 MODEL with but minor modifications.

2.1 Stream Section Delineation

Temperature predictions can be made for one or more connected stream sections during a simulation. The delineation of the stream sections should be based on site, hydrologic, and vegetative characteristics. Ideally, these characteristics should not change significantly along a given reach. For example, the section should not change in aspect. Shading from topography and vegetation should be relatively uniform throughout the section. If a tributary enters a stream, a new section should begin at the point of confluence. Groundwater seepage should remain fairly constant along the section.

The length of the designated stream sections is arbitrary. The model may divide each stream section into two or more sub-sections to keep flow times (the time it takes the water to flow through the section or sub-section) relatively short. This allows a more accurate and simplified accounting of energy transfer rates.

The method of designating stream sections is illustrated in Figure 1. Within the watershed boundaries are an existing clearcut, meadow, and road exposure. The proposed management plan includes two clearcuts. The stream sections (s_i) are identified by establishing a system of nodes (n_i) along the stream system. Nodes are initially placed to delineate obvious changes in site, hydrologic, and vegetative characteristics. For example, nodes n_5 and n_8 were established because the stream passes from forest conditions to more exposed sections. Nodes n_4, n_{12}, and n_{15} were established at points of confluence. Node n_{16} was established at a point where stream aspect changes. Further subdivisions of the stream sections (by establishing more nodes) may be required if field observations indicate a significant change in any of the delineation factors.

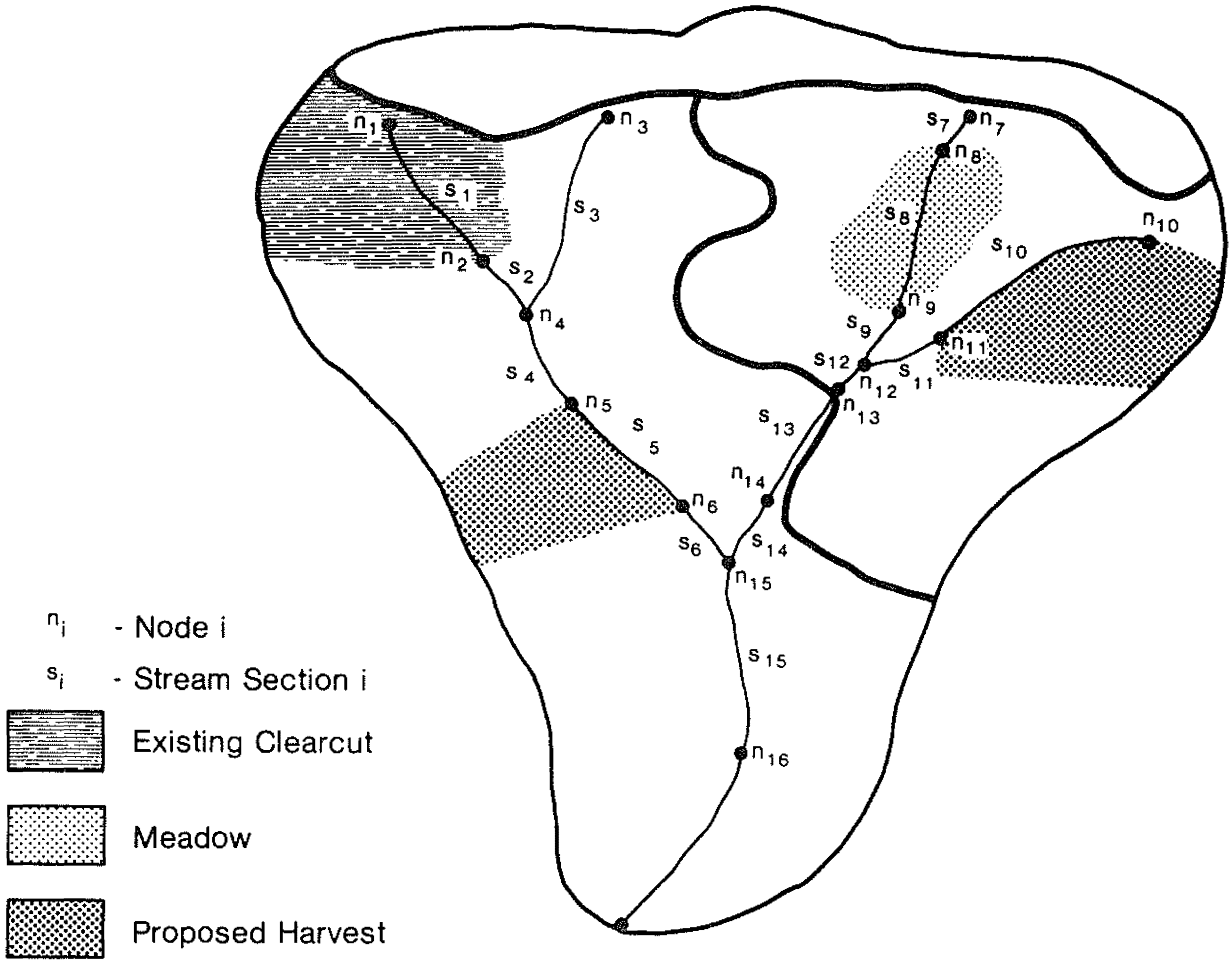


Figure 1. Example of stream section delineation.

2.2 Time Intervals and Water Parcels

Based on calculated instantaneous energy fluxes (Section 2.3), streamflow, and stream surface area, the temperature change for a given time interval is computed for each stream sub-section. The time intervals are chosen to be the stream sub-section's flow time. The time intervals are kept short to assume constant energy transfer rates. Corresponding to each time interval is a discrete water parcel which "flows" through the sub-section during the given time interval. The 24-hour-day is divided into an appropriate number of intervals, each with a corresponding water parcel. A daily simulation of stream temperatures by the model is accomplished by evaluating the energy transfers occurring in each water parcel as it travels downstream.

Temperature calculations are made initially for each water parcel (and thus for a 24-hour period) of the uppermost sub-section of a headwater section. The water parcels are then passed to the next downstream sub-section and the calculations repeated. The calculated output temperature of each water parcel (the parcels input temperature + net heat gain) becomes the input temperatures for the next downstream section. The process is repeated until the inflow of the headwater sections has been routed throughout the stream system. In this manner, the accumulated net heat gains (or losses) of a particular water parcel are accounted for as the parcel travels downstream. The effects of site, hydrologic, and vegetative shading characteristics of each stream section are thus reflected in the calculated stream temperatures.

2.3 The Energy Budget Components

The TEMP-84 MODEL simulates stream temperatures using an energy budget accounting procedure which assesses energy transfers by individual stream sections. The following energy budget components are considered:

(1) net clear-sky solar radiation (HS),
(2) net longwave heat flux (HL),
(3) evaporative heat flux (HE) at the water surface,
(4) convective heat flux (HC) at the air-water interface,
(5) conductive heat flux between bedrock and water (HB), and
(6) the heat flux advected to a stream by groundwater seepage (HADV).

The change in stream temperature, ΔT (°C), for a given time period is based on the calculated instantaneous energy fluxes, streamflow, and stream surface area:

$$\Delta T = \Delta H \, SA \, Q^{-1} \, D^{-1} \, W^{-1} \, K \qquad (1)$$

where: ΔH is the net energy flux (ly s^{-1} = cal cm^{-2} s^{-1})
SA is the stream's surface area (m^2)
Q is the streamflow (ℓ s^{-1})
D is water density (1 g cm^{-3})
W is the heat capacity of water (1 cal g^{-1} $°C^{-1}$)
K = (1 m/ 100 cm) (1000 ℓ/ 1 m^3).

The net energy flux (ΔH) is the sum of the energy budget components. Estimates of each component are determined as follows.

Net solar radiation (HS). Incoming clear-sky radiation (both direct and diffuse components) is computed by first routing potential solar beam radiation through the atmosphere to a plane surface immediately above the forest canopy. The transmissivity and optical air mass of the atmosphere are taken into account. Cloud effects are not considered since the model is designed to simulate potential maximum temperatures. For the direct beam component, the plane surface is assumed to parallel the stream surface to account for the aspect and gradient of the stream. For the diffuse component, the plane surface is assumed to be horizontal. An equation relating diffuse beam radiation to the amount of direct beam radiation incident upon a horizontal surface and the zenith angle to the plane has been developed.

The amount of solar radiation available immediately above the canopy is then routed through the forest canopy. The amount attenuated by passing through the canopy is determined as a function of a canopy cover coefficient and the path length of the radiation through the canopy. Having passed through the canopy, the remaining solar radiation is further reduced to reflect the presence of brush and logs that may overhang the stream and thus provide direct shading for the stream.

The balance of the direct and diffuse beam components available at the stream surface are then distributed into components that are reflected, absorbed, and transmitted by the stream.

Because stream temperatures are intended to be simulated for periods of low flow, it is assumed that the stream would not be transporting suspended solids. Thus, potentially confusing effects from turbidity can be ignored.

Heat conducted to bedrock (HB). Observations by Brown (1969) showed that 15-20% of the net solar radiation reaching the stream bed could be absorbed by bedrock during the day and released back to the stream during the late afternoon and evening hours.

In the TEMP-84 MODEL, it is assumed that all solar radiation entering the stream is absorbed by the water within 20 cm of the water surface. If the stream depth is less than 20 cm, a portion of the solar radiation reaching the water-stream bed interface is absorbed by the bed materials. If the bed is comprised of fine sands, gravels, or cobbles (i.e., particles less than 25 cm in diameter) then the heat capacity and resultant storage of radiation by the bed materials is considered negligible and all of the absorbed radiation is returned directly to the water. (The water surrounding a "small" particle is efficient in recovering the absorbed radiant energy.) If the stream depth is greater than 20 cm, then the composition of bed materials is unimportant and the bed is assumed to have no influence on stream temperatures.

When stream depths are less than 20 cm, that portion of the stream bed comprised of bedrock or boulders (i.e., particle diameters greater than 25 cm) retains the absorbed solar radiation. This energy is stored until net solar radiation levels decrease to values less than or equal to one-half of the daily maximum. At this point storage by the bed materials stops and all stored radiant energy is released at a uniform rate over an 8-hour period.

Calculating storage and release of energy at a water-bedrock interface in this manner should approximate actual energy transfers with minimal data requirements.

Net longwave radiation (HL). The net longwave radiation is the difference of the longwave radiation emitted by the water (the outgoing flux) and the longwave absorbed into the water (the incoming flux). The incoming flux is determined as the sum of the atmospheric longwave radiation and the longwave radiation emitted by the canopy towards the stream.

Clear-sky atmospheric longwave radiation, approximated from an equation developed by Satterlund (1979), is routed, much like the solar radiation, through the forest canopy. The net atmospheric longwave flux is the sum of the flux of clear-sky radiation from the canopy opening above the stream and the atmospheric longwave fluxes that have been attenuated by the forest canopy on the right and left hand sides of the stream. The additional longwave radiation emitted from the canopy on both sides of the channel is added to the net atmospheric flux to approximate the incoming flux available above the channel. This radiation is then routed through the overhanging brush and logs to yield the net incoming flux available at the stream surface.

The difference of the incoming and outgoing fluxes represents longwave radiant energy absorbed by the stream if incoming is greater than outgoing, or released by the stream if outgoing is greater than incoming. Water is nearly opaque to longwave radiation and absorbs longwave radiation within fractions of millimeters below the water surface (Tennessee Valley Authority, 1972). Any net longwave flux entering the water is absorbed by the water, and hence, not routed through the water.

The Stefan-Boltzmann radiation law is the basis for estimating the longwave radiation emitted by the atmosphere, canopy, and the water surface. This equation requires the temperature of the medium in question. In the TEMP-84 MODEL, the temperature of the atmosphere and canopy (including overhanging brush and logs) is assumed to equal the air temperature. Air temperatures may be approximated within the model from daily minimum and maximum air temperatures by means of a sine function.

Satterlund's (1979) equation for calculating the atmospheric longwave radiation requires atmospheric vapor pressure. The atmospheric vapor pressure is computed using

midday relative humidity and midday air temperature estimates. The atmospheric vapor pressure is assumed to be constant throughout the day until the air temperature drops to the point of saturation in which case the atmospheric vapor pressure is assumed to be the saturation vapor pressure at the corresponding air temperature.

Evaporative (HE) and convective (HC) heat flux. The energy required for evaporation to occur at the air-water interface is furnished by the water. This energy is the evaporative heat flux and is computed by a Dalton-type equation utilizing an evaporation rate and the latent heat of vaporization of water. The evaporation rate is a function of the vapor pressure gradient and the wind function recommended by Ryan and Harleman (1976) and Brocard and Harleman (1976). If the vapor pressures of the air and at the water surface are such that condensation occurs, then condensation takes place at the water surface and the heat of condensation (-HE) is released to the stream water.

The convective heat flux is the amount of heat transferred between the water surface and the overlying air due to molecular and turbulent heat conduction. The convective heat flux is calculated using a Bowen ratio approach (Bowen, 1926; Raphael, 1962) which assumes the convective flux is proportional to the evaporative flux. The constant of proportionality (the Bowen ratio) is a function of the temperatures and vapor pressures of the air and water.

Advected energy (HADV). The advected energy component involves the transfer of heat into a given stream section due to the temperature and volume of inflowing groundwater. Groundwater seepage and groundwater temperature are assumed to be constant throughout the stream section. The advected energy effects from groundwater seepage into the stream are determined using a mass balance mixing equation.

2.4 Model Inputs and Outputs

The modeling procedures of TEMP-84 require the following information:

A. General site characteristics
   1. Latitude (degrees)
   2. Longitude (degrees)
   3. Longitude of the center of the local time zone (degrees)
   4. Desired date for the simulation (mm/dd)
   5. Mean elevation of the site (m)

6. Midday (1300 hours) relative humidity for the date (%)
7. Estimated windspeed at the stream surface (m s^{-1})

B. Stream characteristics for each section
   1. Stream aspect (degrees clockwise from north)
   2. Stream gradient (%)
   3. Length of the stream section (m)
   4. Average width of the water (m)
   5. Average velocity of the water (m s^{-1})
   6. Percent of the stream that
      a) is less than 20 cm deep, and
      b) the bed materials are comprised of bedrock and non-protruding boulders greater than 25 cm in diameter.
   7. Inflow (ℓ s^{-1}) and water temperature (°C) for headwater sections
   8. Inflow (ℓ s^{-1}) and water temperature (°C) for tributaries
   9. Groundwater seepage (ℓ s^{-1} per 100 m of channel) and temperature (°C)
   10. Maximum and minimum daily air temperatures (°C)

C. Shading characteristics for each section
   1. Average angles of topographic and forest shading to the southeast, south, and southwest (degrees)
   2. Average hillslope and forest shading angles measured perpendicular to the stream axis on the right and left sides of the channel (degrees)
   3. Canopy cover coefficient for forest vegetation on both sides of the channel (decimal fraction)
   4. Forest vegetation height on each side of the channel (m)
   5. Buffer strip width for each side of the channel (m)
   6. Percent of the stream section shaded directly by overhanging brush and logs.

The model's output consists of tables and graphs of each stream section's inflow and outflow temperatures and tables of the calculated energy budget components.

3.0 USER INSTRUCTIONS

This section contains the information a user needs to successfully assimilate the required input data and execute the TEMP-84 MODEL. Discussions of input data, specific input formats, data set structure, model execution, and model outputs are presented.

It is assumed that the user has a basic knowledge of accessing the FCCC Univac, Executive Control Language (ECL) commands, concepts of data and program files, obtaining and routing output (including plots from a Calcomp plotter), and FORTRAN format editing codes. If this is not the case, your computer specialist can answer your questions and/or direct you to the appropriate information source.

3.1 Overview of Data Inputs and Input Options

Data inputs for the TEMP-84 MODEL are classified as site characteristics or stream and shading characteristics for each section. Site characteristics are assumed to have the same value for each of the stream sections on the site. Stream and shading characteristics are assumed particular to a specific stream reach.

Site Characteristics. Site characteristics include the desired date of the simulation, the estimated relative humidity and windspeed corresponding to the desired date, the mean elevation, latitude and longitude of the site, and the longitude of the center of the local time zone. The date of the simulation should correspond to those items that are associated with it, e.g., flow values and air temperatures. Relative humidity for the selected date is estimated for 1300 hours local standard time. Windspeed is assumed constant and should represent the average windspeed at the stream surface. The mean elevation of the site is used as the mean elevation of each stream section. The latitude of the site, along with the solar declination, determines the position of the sun at a given time for the selected date. The solar declination, and thus the solar altitude and azimuth, is particular to the selected date and is computed from site characteristics inputs. The longitude of the site and longitude at the center of the local time zone are necessary to adjust between mean solar and local time. Again, these input items are assumed to have the same value for each stream section at the site.

In addition, daily air temperatures and the amount of groundwater seepage and/or groundwater temperature may be relatively constant among most of the stream sections. Thus, an option is provided to allow daily air temperature values, groundwater seepage, and groundwater temperature to be entered as site characteristics. These values will be

the default values. That is, when air temperature or groundwater seepage or groundwater temperature is not explicitly specified for a particular stream section, the corresponding value entered as a site characteristic will be used.

Stream Characteristics for Each Section. The stream characteristics for each section are the physical properties of the stream section, the section's flow properties, and the daily air temperatures at the stream section.

The physical properties of the stream section include stream aspect, gradient, length and width, water velocity, and the composition of the stream bed. The aspect of the stream section is the angle in degrees measured clockwise from north to an imaginary vector directed downstream. The stream section aspect allows the model to determine from which side of the stream the sun is shining which enables the correct selection of those parameters that are side dependent (e.g., buffer widths and canopy cover coefficients). The aspect and gradient determine the orientation of the stream relative to the sun. The length and width of the stream section determine its surface area, an important factor in calculating the temperature gain (or loss) of the water. The width value should be representative of the average width of the stream through the section excluding stagnant pools and protruding boulders. The number of sub-sections a given stream section is divided into is a function of the water velocity through the stream section and the section length. To determine the effects of energy stored by the bed materials and later conducted back to the water, the model requires an estimate of that portion of the stream section that meets both of the following criteria: (1) stream depth is less than 20 cm, and (2) the bed materials are comprised of bedrock and non-protruding boulders greater than 25 cm in diameter.

The section's flow properties include section inflow (streamflow at the beginning of the section), groundwater seepage, and inflow from tributaries. Section inflow and inflow temperatures are required by the model for each stream section. Section inflow is assumed to be constant. The inflow temperatures represent the temperature of the water at discrete time intervals. There are 96 time intervals, each 15 minutes in length and each beginning 15 minutes after the previous interval. Each headwater section requires an inflow and associated temperature estimate. For those sections downstream from a headwater, inflow and inflow temperatures may be calculated by the model (i.e., the outflow and outflow temperatures of the section immediately upstream), or, may be user supplied. Inflow temperatures may be input in one of the following ways:

(1) one temperature value representing average daily water temperature,

(2) 96 temperature values representing the water temperature at successive 15 minute intervals beginning at 0015 hours,

(3) 48 temperature values representing the water temperature at successive 30 minute intervals beginning at 0030 hours, or

(4) 24 temperature values representing the water temperature at successive 60 minute intervals beginning at 0100 hours.

If method (3) or (4) is selected, the model interpolates linearly between two successive values to obtain temperature values at 15 minute intervals.

In general, the water temperature for headwater sections is relatively constant and method (1) will be used to input inflow temperatures. Methods (2), (3), and (4) allow the simulation to begin at any point in the stream system. This is useful if, for example, you are interested in only the lower reaches of a stream. In this case it may be prudent to measure stream temperatures at the desired beginning point rather than allow the model to compute the required temperatures from many upstream sections that would require more resources for data collection. Also, these methods provide a means of prohibiting any errors in the calculated stream temperatures for upstream sections from being propagated beyond the point at which inflow temperatures are user supplied. Thus, a more accurate simulation is accomplished where "long" or "complex" stream systems are involved.

If groundwater seepage, either into or out of the stream, is a factor for the stream section, the amount of groundwater seepage per 100 meters of channel needs to be determined. The amount of seepage is added to section inflow to compute section outflow. If the seepage is into the channel then the temperature and amount of seepage determines the energy advected into the stream by groundwater. The temperature of the seepage is assumed to be constant throughout the stream section. When groundwater seepage and/or temperature is relatively uniform among stream sections, these values may be entered as site characteristics. In this case, indicating that groundwater is a factor but omitting the groundwater seepage or temperature value will be the signal to the model to use the "default" values which were entered as site characteristics.

When a tributary enters a stream section, and if no sections of the tributary are of interest, then to reduce the resources required for data collection and the propagation of errors by the model, you may provide the flow and water temperature of the tributary and allow the model to calculate the resultant flow and water temperatures of the stream below the confluence. Tributary flow is assumed to be constant. The water temperatures of the tributary may be provided in the same way as section inflow temperatures (i.e., daily average or one-quarter, one-half, or hourly intervals).

Calculation of the net longwave radiation and evaporative (and hence convective) flux requires estimated daily air temperatures at each stream section. Ultimately, the model requires an air temperature value for each of 96 fifteen minute intervals. The method used to supply these air temperature values to the model may be one of the following.

You may provide a daily minimum and maximum air temperature and allow the model to approximate air temperatures in 15 minute intervals by means of a sine function (Equation (64), Section 4.5). The minimum and maximum values are assumed to occur at 0400 and 1600 hours local standard time, respectively. Alternatively, you may supply air temperature values in one-quarter, one-half, or hourly intervals beginning at 0015, 0030, or 0100 hours, respectively. If one-half or hourly intervals are selected the model will interpolate linearly to obtain the remaining required values.

If the air temperature is relatively uniform among stream sections, these values may be entered as site characteristics. In this case, omitting the air temperature values for any given stream section will be the signal to the model to use the "default" values which were entered as site characteristics.

Shading Characteristics for Each Section. The shading characteristics of a stream section include topographic and forest shade angles, hillslope and perpendicular forest shade angles, forest canopy characteristics, and any direct, continuous shading provided to the stream.

Representative topographic and forest shade angles (Figure 2) are required in the directions of southeast, south, and southwest. The topographic shade angles are measured from the horizontal at the stream surface up to the topographic features that will obstruct the sun. The forest shade angles are measured from the horizontal at the stream surface up to the top of the edge of the forest canopy. For the purposes of the TEMP-84 MODEL, southeast is from due north to 30° east of due south, south is from 30° east to 30° west of due south, and southwest is from 30° west of due south to due north. These angles are important in determining when the sun is above any obstructing topography, and if so, is it shining directly on the stream or does the direct beam radiation need to be routed through the forest canopy. The angles selected for these comparisons are determined by the solar azimuth. For example, if the solar azimuth is 90° (due east), then the appropriate topographic and forest shade angles are those to the southeast. A knowledge of the approximate solar altitude and azimuth at different times of the day will be helpful in estimating these angles.

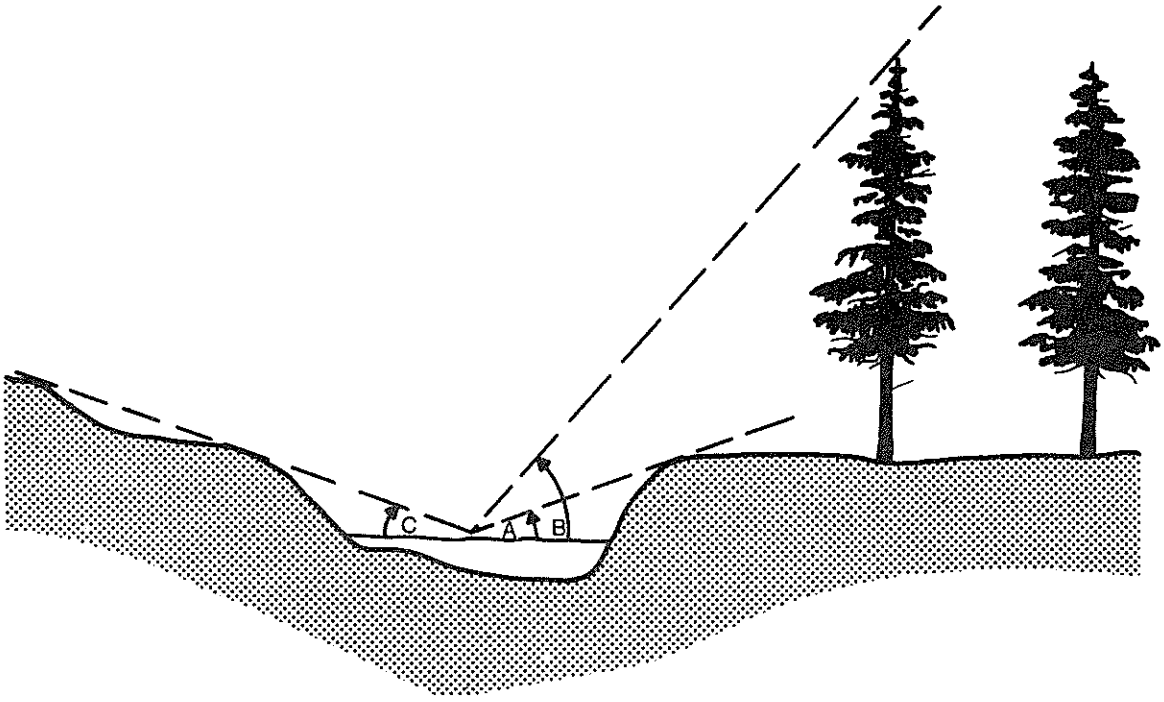


Figure 2. Schematic of (A) topographic shading, (B) forest shading, and (C) hillslope angles.

Perpendicular forest shade angles are measured similar to the forest shade angles mentioned above. These angles represent the angle from the stream surface to the top edge of the canopy measured perpendicular to the longitudinal axis of the stream. Similarly, hillslope angles are the average angle of the hillslope measured from the horizontal perpendicular to the longitudinal axis of the stream (Figure 2). The hillslope angles are important for spatially locating the forest canopy with respect to the stream channel. (Note in Figure 2 that the hillslope angle on the right side of the channel is essentially zero.) These angle estimates are required for both the right and left hand sides of the stream section. For the purpose of the TEMP-84 MODEL, the right and left hand sides of the stream are to the observers right and left, respectively, when facing downstream.

The required forest canopy characteristics are a canopy cover coefficient, average tree height, and buffer strip width. These characteristics must be estimated for both the right and left hand sides of the stream. The canopy cover coefficient reflects the amount of energy that is allowed to pass directly through the forest canopy without being intercepted by the canopy. It is used in the energy attenuation process (Equation (11) and Section 4.3) when routing energy through the canopy. Average tree heights and

perpendicular forest shade angles determine the size of the canopy opening directly above the stream and are also used to compute the attenuation of energy by the canopy. The buffer strip widths, hillslope angles, and forest shade angles determine the path length of any radiation being routed through the forest canopy. Buffer strip widths are assumed to be measured along the horizontal, not the hillslope.

An estimate of the percent of the stream section that is provided direct, continuous shading by overgrowth, logs, etc. is required. The model assumes this shading is in effect throughout the day and adjusts the solar and longwave radiation components accordingly.

Section identification. To carry out the simulation of stream temperatures, the model must be able to identify each stream section in respect to its position relative to the other stream sections. To make this identification possible, a specific set of rules must be followed.

(1) Each stream section must be identified by an upstream node and a downstream node. The nodes are represented by a 1 or 2 character identifier. The model does not distinguish between leading and trailing blanks embedded in node identifiers. That is, the node identifier " A" is the same as "A ".

(2) Each stream section is either a headwater section or is downstream from a headwater section. A headwater is a stream section whose inflow is assumed to originate from a point source at the uppermost point of the section. Each headwater must have an upstream node identifier of "HW". All other node identifiers must be unique. No stream section may have a downstream node identifier of "HW".

(3) There must be at least one section identified as a headwater section (i.e., an upstream node identifier of "HW").

(4) Each section's downstream node identifier must be identical to the upstream node identifier of the section immediately downstream.

(5) There can be at most 3 stream sections with a common downstream node.

(6) There can be only one stream section that does not have another section immediately downstream.

3.2 Output Options

TEMP-84 output is designed to be routed to high speed printers. Many of the outputs require more than 80 columns per line. In addition, the page headers (title, date, and page number) will appear only if the output is printed on a high speed printer.

Site Output. The only mandatory output is the site input data summary page (Figure 3). This output consists of a one page summary of the site input data. Included are site default values entered for groundwater seepage and temperature and air temperatures.

Other site outputs that are optional are a printer plot of the stream system (Figure 4) and a table of solar altitudes and solar azimuths for the simulation date (Figure 5). The plot of the stream system is useful in verifying the relative positions and lengths of the stream sections. This plot occupies 1-2 pages of output depending on the selected scale. The table of solar altitudes and solar azimuths gives the relative position of the sun at 15 minute intervals. The reported altitude is in degrees from the horizontal at the indicated time. The reported azimuth is in degrees clockwise from north at the indicated time and altitude. This table occupies one page of output.

Each site output page has a header containing 40 characters of information you supply, the current version of the TEMP-84 MODEL, the execution date, and the page number.

Section output. The model's output for each section may consist of a summary of the section input, a table of the section's water temperatures, and printer plots of the input and output temperatures and the change in temperature. Also available are Calcomp plotter versions of the printer plots.

The section input summary (Figure 6) consists of the input data supplied by you for the stream section as well as other parameters that are required that may have been calculated by the model. These calculated parameters include section flow time--the time it takes the water to flow through the section, the number of sub-sections the model divided the stream section into, the sub-section flow time, the accumulated flow time--the time it has taken the water to flow from its originating source to the beginning of this section, and the average depth of the section. Also reported are the section's air temperatures and inflow characteristics. The inflow characteristics include a table of section inflow temperatures (Figure 7). These temperatures are either the calculated water temperatures after mixing the outflow of the immediate upstream sections or the user supplied inflow temperatures. They do not include the temperatures of the inflow from a tributary. The times reported in this table correspond to the output times of the first section processed of those immediately upstream. The first time value is equal to the reported accumulated flow time plus 15 minutes and adjusted to begin closest to but after 2400 hours. The section input summary occupies 1-4 pages of output.

The table of stream section water temperatures (Figure 8) includes the input temperatures and corresponding times, the output temperatures and corresponding times,

EXAMPLE DATASET FOR THE EXECUTION OF TEMP-84
40 COLUMNS FOR A PAGE HEADER TO APPEAR HERE

SITE CHARACTERISTICS :

LATITUDE - 38.0
LONGITUDE - 118.0
ELEVATION - 2100. M
DATE OF PREDICTION (MMDD) -0827
MIDDAY RELATIVE HUMIDITY - 40.0 %
AVERAGE WIND SPEED AT STREAM SURFACE - 1.0 M/S

ALL TIMES ARE DAYLIGHT SAVINGS TIMES RELATIVE
TO THE TIME ZONE CENTERED AT 120 DEGREES LONGITUDE

SITE DEFAULTS :

GROUND WATER SEEPAGE (PER 100 M) - 1.00 L/S
GROUND WATER TEMPERATURE - 7.0 C
AIR TEMPERATURES :
USER SUPPLIED IN 30 MINUTE INTERVALS

TIME	TEMP	TIME	TEMP	TIME	TEMP	TIME	TEMP
0015	6.1	0030	5.7	0045	5.6	0100	5.4
0115	5.4	0130	5.5	0145	5.6	0200	5.7
0215	5.5	0230	5.3	0245	5.6	0300	5.8
0315	5.7	0330	5.5	0345	5.6	0400	5.6
0415	5.1	0430	4.7	0445	4.8	0500	4.8
0515	4.7	0530	4.6	0545	4.6	0600	4.6
0615	4.8	0630	5.0	0645	5.3	0700	5.6
0715	5.9	0730	6.2	0745	7.5	0800	8.9
0815	10.9	0830	12.9	0845	14.3	0900	15.7
0915	20.2	0930	24.7	0945	25.6	1000	26.5
1015	26.6	1030	26.8	1045	25.9	1100	24.9
1115	23.0	1130	21.1	1145	21.4	1200	21.8
1215	23.7	1230	25.6	1245	24.3	1300	22.9
1315	21.7	1330	20.5	1345	20.2	1400	19.8
1415	19.8	1430	19.8	1445	19.5	1500	19.3
1515	18.4	1530	17.5	1545	16.8	1600	16.2
1615	14.5	1630	12.8	1645	12.4	1700	12.1
1715	11.6	1730	11.1	1745	10.7	1800	10.3
1815	10.0	1830	9.8	1845	9.6	1900	9.4
1915	9.2	1930	9.0	1945	8.7	2000	8.3
2015	7.8	2030	7.3	2045	7.2	2100	7.0
2115	7.3	2130	7.5	2145	7.0	2200	6.5
2215	6.4	2230	6.3	2245	6.3	2300	6.3
2315	6.3	2330	6.4	2345	6.4	2400	6.5

Figure 3. Site input data summary page.

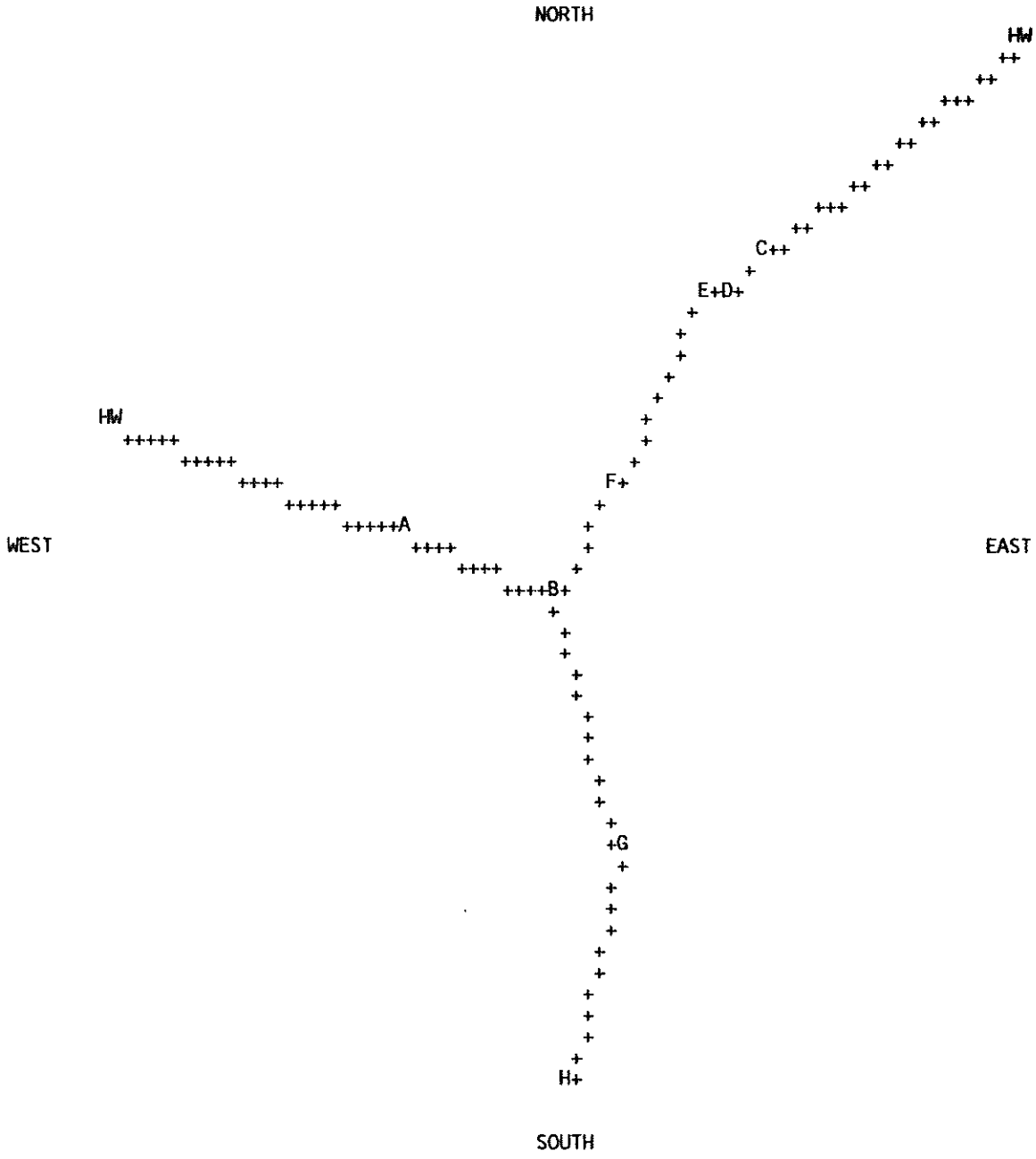


Figure 4. Stream system plot.

TABLE OF SOLAR ALTITUDES AND SOLAR AZIMUTHS
FOR 08/27
DECLINATION 9.5 DEGREES
LATITUDE 38.0
LONGITUDE 118.0

TIME	0015	0030	0045	0100	0115	0130	0145	0200
ALTITUDE	-42.0	-42.3	-42.5	-42.4	-42.0	-41.4	-40.5	-39.4
AZIMUTH	349.8	354.7	359.7	4.7	9.7	14.6	19.4	24.0
TIME	0215	0230	0245	0300	0315	0330	0345	0400
ALTITUDE	-38.1	-36.6	-34.9	-33.1	-31.1	-29.0	-26.7	-24.4
AZIMUTH	28.4	32.7	36.7	40.6	44.3	47.8	51.1	54.3
TIME	0415	0430	0445	0500	0515	0530	0545	0600
ALTITUDE	-21.9	-19.4	-16.8	-14.1	-11.4	-8.7	-5.9	-3.0
AZIMUTH	57.3	60.2	62.9	65.6	68.2	70.7	73.1	75.5
TIME	0615	0630	0645	0700	0715	0730	0745	0800
ALTITUDE	-.1	2.8	5.7	8.6	11.6	14.5	17.5	20.4
AZIMUTH	77.8	80.1	82.4	84.6	86.9	89.2	91.5	93.9
TIME	0815	0830	0845	0900	0915	0930	0945	1000
ALTITUDE	23.4	26.3	29.2	32.1	34.9	37.7	40.5	43.2
AZIMUTH	96.3	98.8	101.3	104.0	106.9	109.9	113.0	116.5
TIME	1015	1030	1045	1100	1115	1130	1145	1200
ALTITUDE	45.8	48.3	50.7	52.9	55.0	56.8	58.4	59.7
AZIMUTH	120.2	124.1	128.5	133.3	138.5	144.2	150.4	157.2
TIME	1215	1230	1245	1300	1315	1330	1345	1400
ALTITUDE	60.7	61.3	61.5	61.3	60.8	59.8	58.5	57.0
AZIMUTH	164.4	171.9	179.6	187.3	194.9	202.1	208.9	215.2
TIME	1415	1430	1445	1500	1515	1530	1545	1600
ALTITUDE	55.2	53.1	50.9	48.5	46.0	43.5	40.8	38.0
AZIMUTH	220.9	226.2	231.0	235.4	239.4	243.2	246.6	249.8
TIME	1615	1630	1645	1700	1715	1730	1745	1800
ALTITUDE	35.2	32.4	29.5	26.6	23.7	20.7	17.8	14.8
AZIMUTH	252.8	255.7	258.4	261.0	263.5	265.9	268.3	270.6
TIME	1815	1830	1845	1900	1915	1930	1945	2000
ALTITUDE	11.9	8.9	6.0	3.1	.2	-2.7	-5.6	-8.4
AZIMUTH	272.9	275.1	277.4	279.7	282.0	284.3	286.7	289.1
TIME	2015	2030	2045	2100	2115	2130	2145	2200
ALTITUDE	-11.1	-13.9	-16.5	-19.1	-21.7	-24.1	-26.5	-28.7
AZIMUTH	291.6	294.1	296.8	299.5	302.4	305.4	308.6	311.9
TIME	2215	2230	2245	2300	2315	2330	2345	2400
ALTITUDE	-30.9	-32.9	-34.8	-36.5	-38.0	-39.3	-40.4	-41.3
AZIMUTH	315.4	319.0	322.9	326.9	331.1	335.6	340.1	344.9

Figure 5. Table of solar altitudes and azimuths.

```
40 COLUMNS FOR A PAGE HEADER   SECTION 8   B-> G   TEMP-84 (JUL 1984)  DATE 082884  PAGE 4

STREAM SECTION   8
     UPSTREAM NODE -  B
     DOWNSTREAM NODE -  G
     B -> G - CONFLUENCE AT B

STREAM SECTION CHARACTERISTICS :

     ASPECT - 170 DEGREES
     LENGTH -     600. M
     WIDTH -   1.8 M
     AVERAGE VELOCITY -     .10 M/S
     GRADIENT -    8. %
     DEPTH < 20 CM AND BED > 25 CM -  10. %

CALCULATED:

     AVG DEPTH -  36.6 CM
     SECTION FLOW TIME -  100 MIN
     ACCUMULATED FLOW TIME -  0 HRS 50 MIN
     NUMBER OF SUB-SECTIONS -     7
     SUB-SECTION FLOW TIME - 14.3 MIN
     SUB-SECTION LENGTH -   85.7 M
     SUB-SECTION SURFACE AREA -   150.0 SQ M
     SUB-SECTION GROUND WATER SEEPAGE -    .00 L

SHADING CHARACTERISTICS :

     TOPOGRAPHIC    SE   9.
     SHADE ANGLES   S   19.
                    SW  25.

     HILLSLOPE      R   29.
     ANGLES         L   18.

                    SE  60.
     FOREST SHADE   S   60.
     ANGLES         SW  70.
                    R   70.
                    L   75.

     CANOPY COVER   R     .60
     COEFFICIENT    L     .70

     VEGETATION     R    40.0
     HEIGHT (M)     L    42.0

     % SHADED BY BRUSH/LOGS -    20.

     BUFFER STRIP WIDTH:
       RIGHT SIDE - INFINITE (CONTINUOUS FOREST)
       LEFT  SIDE - INFINITE (CONTINUOUS FOREST)

AIR TEMPERATURES :

     USED SITE DEFAULT AIR TEMPS
```

Figure 6. Section input summary.

INFLOW CHARACTERISTICS :

SECTION INFLOW - 64.0 L/S (FROM UPSTREAM SECTIONS)
TRIBUTARY INFLOW - NONE CONSIDERED
GROUND WATER SEEPAGE - NONE CONSIDERED

Q AT NODE B - 64.00 L/S
Q AT NODE G - 64.00 L/S
AVERAGE Q - 64.00 L/S

INFLOW TEMPERATURES :

GROUND WATER - NONE CONSIDERED
TRIBUTARY TEMPS - NONE CONSIDERED
SECTION INFLOW TEMPS ACCUMULATED FROM UPSTREAM SECTIONS

TEMPERATURES OF SECTION INFLOW (DEG C)

TIME	TEMP	TIME	TEMP	TIME	TEMP	TIME	TEMP
0005	7.8	0020	7.8	0035	7.6	0050	7.5
0105	7.4	0120	7.3	0135	7.2	0150	7.2
0205	7.1	0220	7.1	0235	7.1	0250	7.1
0305	7.0	0320	7.0	0335	7.0	0350	6.9
0405	6.9	0420	6.9	0435	6.8	0450	6.8
0505	6.7	0520	6.7	0535	6.7	0550	6.7
0605	6.7	0620	6.6	0635	6.6	0650	6.6
0705	6.6	0720	6.7	0735	6.8	0750	7.1
0805	7.4	0820	7.6	0835	8.0	0850	8.4
0905	8.8	0920	9.2	0935	9.7	0950	10.1
1005	10.6	1020	11.1	1035	11.5	1050	11.9
1105	12.3	1120	12.6	1135	12.9	1150	13.3
1205	13.5	1220	13.8	1235	14.0	1250	14.3
1305	14.5	1320	14.7	1335	14.9	1350	14.9
1405	14.7	1420	14.6	1435	14.6	1450	14.5
1505	14.2	1520	13.9	1535	13.6	1550	13.4
1605	13.0	1620	12.6	1635	11.8	1650	11.4
1705	11.2	1720	11.0	1735	10.8	1750	10.5
1805	10.4	1820	10.1	1835	9.9	1850	9.7
1905	9.6	1920	9.4	1935	9.3	1950	9.2
2005	9.1	2020	9.0	2035	8.9	2050	8.8
2105	8.7	2120	8.6	2135	8.6	2150	8.5
2205	8.4	2220	8.3	2235	8.2	2250	8.2
2305	8.1	2320	8.0	2335	8.0	2350	7.9

Figure 7. Section inflow characteristics.

STREAM TEMPERATURES DEGREES CELSIUS					ENERGY BUDGET COMPONENTS (SUB-SECTION AVG IN LANGLEYS/MINUTE)						
AT NODE B TIME	TEMP	AT NODE G TIME	TEMP	DELTA	NET SOLAR	NET BEDRCK	NET LONGWAVE	EVAP	CONV	H (LY/SEC)	ADVECTED (DEG C)
0020	7.78	0200	7.55	-.23	.000	.000	-.072	-.006	-.005	-.0014	.000
0050	7.54	0230	7.31	-.22	.000	.000	-.071	-.005	-.005	-.0013	.000
0120	7.31	0300	7.09	-.21	.000	.000	-.069	-.005	-.004	-.0013	.000
0150	7.22	0330	7.01	-.21	.000	.000	-.068	-.004	-.004	-.0013	.000
0220	7.13	0400	6.93	-.21	.000	.000	-.068	-.004	-.004	-.0013	.000
0250	7.06	0430	6.85	-.20	.000	.000	-.067	-.004	-.004	-.0012	.000
0320	6.98	0500	6.77	-.21	.000	.000	-.068	-.005	-.004	-.0013	.000
0350	6.91	0530	6.69	-.22	.000	.000	-.069	-.005	-.005	-.0013	.000
0420	6.88	0600	6.66	-.22	.000	.000	-.071	-.006	-.005	-.0014	.000
0450	6.80	0630	6.58	-.22	.000	.000	-.071	-.005	-.005	-.0014	.000
0520	6.73	0700	6.52	-.21	.002	.000	-.070	-.005	-.005	-.0013	.000
0550	6.67	0730	6.48	-.18	.008	.000	-.067	-.004	-.004	-.0011	.000
0620	6.61	0800	6.49	-.13	.021	.000	-.063	-.002	-.002	-.0008	.000
0650	6.58	0830	6.57	-.01	.046	.000	-.053	.001	.002	-.0001	.000
0720	6.66	0900	6.82	.16	.085	.000	-.039	.004	.009	.0010	.000
0750	7.05	0930	7.44	.38	.139	.000	-.020	.005	.017	.0023	.000
0820	7.64	1000	8.31	.66	.203	-.001	.008	.003	.029	.0041	.000
0850	8.35	1030	9.27	.92	.269	-.001	.032	.000	.037	.0056	.000
0920	9.22	1100	10.35	1.13	.327	-.001	.048	-.004	.041	.0069	.000
0950	10.13	1130	11.33	1.20	.362	-.001	.044	-.007	.039	.0073	.000
1020	11.06	1200	12.15	1.09	.349	-.001	.027	-.010	.032	.0066	.000
1050	11.86	1230	13.46	1.60	.559	-.002	.013	-.013	.027	.0098	.000
1120	12.61	1300	14.74	2.13	.767	-.003	.005	-.017	.024	.0130	.000
1150	13.26	1330	15.96	2.70	.989	-.004	-.002	-.021	.022	.0165	.000
1220	13.77	1400	16.21	2.44	.909	.000	-.010	-.024	.019	.0149	.000
1250	14.25	1430	16.05	1.79	.688	.001	-.022	-.025	.015	.0109	.000
1320	14.71	1500	15.86	1.15	.462	.001	-.030	-.025	.012	.0070	.000
1350	14.95	1530	15.70	.76	.324	.001	-.035	-.025	.010	.0046	.000
1420	14.63	1600	15.27	.65	.288	.001	-.038	-.023	.009	.0040	.000
1450	14.47	1630	14.95	.48	.234	.001	-.045	-.023	.007	.0029	.000
1520	13.88	1700	14.17	.30	.176	.001	-.053	-.020	.004	.0018	.000
1550	13.38	1730	13.48	.10	.111	.001	-.060	-.018	.001	.0006	.000
1620	12.59	1800	12.55	-.04	.064	.001	-.064	-.014	-.001	-.0002	.000
1650	11.42	1830	11.32	-.10	.033	.001	-.062	-.010	-.001	-.0006	.000
1720	10.99	1900	10.84	-.15	.018	.001	-.063	-.008	-.001	-.0009	.000
1750	10.55	1930	10.38	-.17	.010	.001	-.064	-.006	-.002	-.0010	.000
1820	10.06	2000	9.88	-.18	.004	.001	-.063	-.005	-.002	-.0011	.000
1850	9.73	2030	9.54	-.19	.000	.001	-.064	-.004	-.002	-.0011	.000
1920	9.39	2100	9.20	-.20	.000	.001	-.066	-.004	-.003	-.0012	.000
1950	9.21	2130	9.00	-.21	.000	.001	-.069	-.005	-.004	-.0013	.000
2020	8.99	2200	8.78	-.21	.000	.001	-.069	-.005	-.004	-.0013	.000
2050	8.83	2230	8.61	-.22	.000	.001	-.070	-.005	-.005	-.0013	.000
2120	8.62	2300	8.41	-.22	.000	.000	-.070	-.005	-.005	-.0013	.000
2150	8.48	2330	8.26	-.22	.000	.000	-.071	-.006	-.005	-.0014	.000
2220	8.33	2400	8.11	-.22	.000	.000	-.071	-.006	-.005	-.0014	.000
2250	8.15	0030	7.94	-.22	.000	.000	-.070	-.005	-.004	-.0013	.000
2320	7.98	0100	7.76	-.22	.000	.000	-.070	-.005	-.005	-.0013	.000
2350	7.89	0130	7.67	-.22	.000	.000	-.071	-.006	-.005	-.0014	.000

Figure 8. Table of section input and output stream temperatures and energy budget components in 30 minute intervals.

and the change in temperature. The input temperatures (the temperatures at the upstream node) are the water temperatures resulting from combining the temperatures described as inflow characteristics above with the inflow temperatures of a tributary (if a tributary is present). The output temperatures (the temperatures at the downstream node) are the net result of adding the flux of the energy budget components to the input temperatures. The output times are equal to the input times plus the section flow time. This table may be reported in 15, 30, or 60 minute intervals and may or may not include the energy budget components. For each energy budget component, positive values indicate energy available to the stream while negative values indicate an energy loss. The entries in the columns labeled NET SOLAR, NET LONGWAVE, EVAP, CONV, and ADVECTED are the component's average value through the stream section with each sub-section's value being calculated by Equations (31), (45), (46), (55), and (56) of Section 4.2, respectively. In the column labeled NET BEDRCK, negative values are the average of each sub-section's value calculated by Equation (32). Positive values represent averages of that portion of the total energy that was stored by the bed that is being released back to the stream over an eight hour period. The negative values are included for inspection only and are set equal to zero for the calculation of ΔT in Equation (57). The column labeled H is the sum of the energy budget components (H = NET SOLAR + NET BEDRCK + NET LONGWAVE + EVAP + CONV), again, with negative values of NET BEDRCK set to zero. These values are included in the output to be used in evaluating data sensitivities (Section 5.0). The units for H are langleys per second so no conversion is necessary for the data sensitivity equations. This table occupies 1-2 pages of output.

The plots of section input and output water temperatures (Figure 9) and change in water temperature (Figure 10) are simply a graphical representation of the tabular data in Figure 8. The plotted points in Figure 9 represent the corresponding time and temperature values of the input and output times and temperatures in the table. In Figure 10, the plotted points represent the change in temperature at the output time in the table (the time at the downstream node). The printer plots occupy one page of output for each plot. The Calcomp plots are drawn in an 8 x 6 inch area within an 11 x 8 1/2 inch frame and are stacked in groups of three with each stack beginning immediately on the right of the previous stack (e.g., nine plots would be formatted in 3 stacks, each 11 inches wide and 25 1/2 inches tall).

Each section output page has a header containing the section's upstream node identifier, downstream node identifier, and the same information as in the site page header.

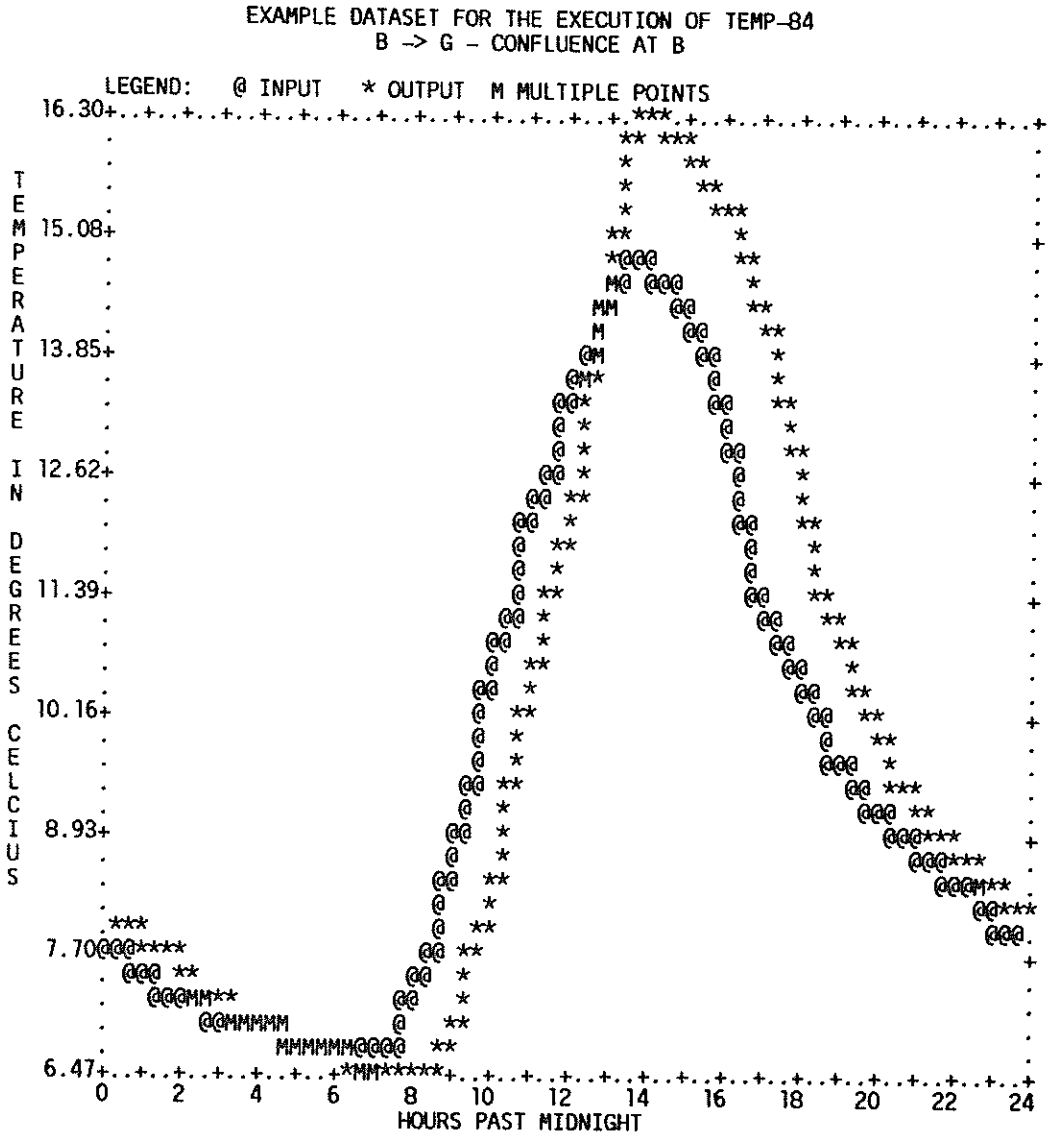


Figure 9. Printer plot of stream section input and output temperatures.

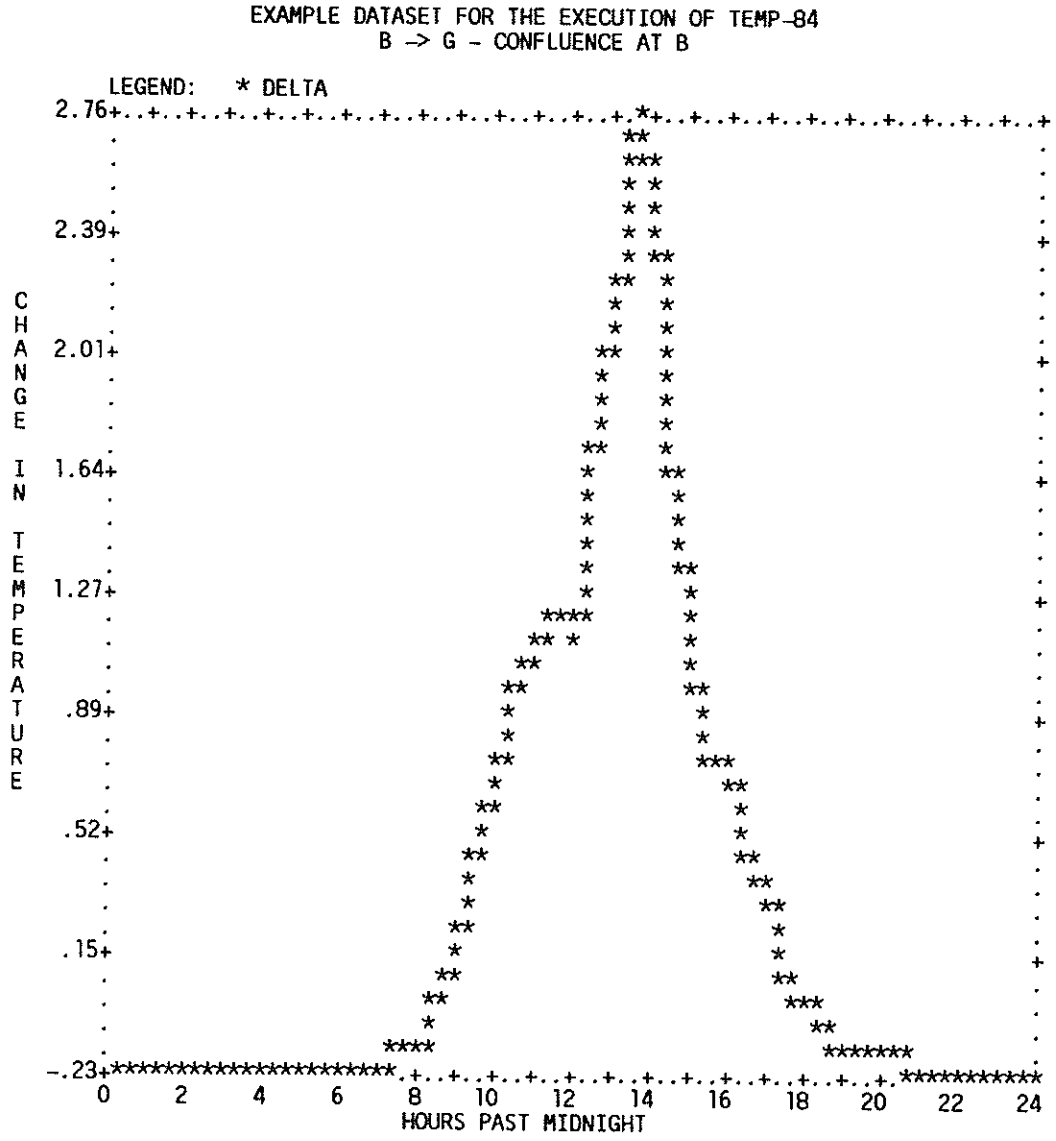


Figure 10. Printer plot of the change in temperature for the section.

3.3 Input Requirements and Formats

TEMP-84 input data is structured as 80 column records (i.e., in card image format). Each record is classified as either site data or (stream) section data. Site data records contain information that is uniform for each identified stream section (e.g., latitude). Section data records contain information that is particular to the given stream section (e.g., section length).

The input data for a simulation must include one set of site data records and one or more sets of section records (one set for each identified stream section). The site data records must appear first, followed by the sets of section data records. The sequential order of the sets of section data is arbitrary.

If you want to simulate stream temperatures for another stream system, its site and section data records may follow the last record of the last set of section data for the previous site. In this way, input data for as many stream systems as desired can be arranged in the same data set (i.e., the site and section data records for the system followed by the same sequence for the next system).

The format specified for some of the following records is free field. Free field format simply means that input values are not restricted to certain columns of the record. The only requirements are (1) a value must be entered (blanks are <u>not</u> a valid entry), (2) the entered values be separated by one or more spaces, (3) each value must end in or before column 80, and (4) each 80 column record may contain one or more values with the remaining values following directly in the next 80 column record. The format specification will further designate the values as floating point or integer. A floating point designation means decimal points may be included in the value. The decimal point is required only to separate significant digits to the right of the decimal. That is, for free field floating point, the number 10.0 may be entered as 10, however, the number 10.5 <u>must</u> be entered as 10.5 (i.e., with the decimal point). An integer designation means the expected number is a "whole" number and a decimal point is not allowed.

3.3.1 Site Data Records

A set of site data consists of at least four records--a site identifier record, a site characteristics record, a record to supply site default groundwater seepage and/or temperature and to indicate if site default air temperatures will be input (a site default options record), and a record to select certain output (a site output options record). If

site default air temperatures are to be input the remainder of the site data consists of as many records as required to supply these values. There must be only one set of site data records included in the data set for each stream system to be simulated.

Site identifier record. The site identifier record should include a description of the site (e.g., location, watershed name, etc.). This record appears in the site output page and in the title of the plots.

READ TITLE
FORMAT (A80)

COLUMNS	DESCRIPTION
1-80	Enter up to 80 characters of identifying information for this site. Format - A80.

Site characteristics record. The site characteristics record contains the mean latitude and longitude of the site, the longitude of the center of the local time zone, an indicator for daylight savings time, the desired date of the simulation, the mean elevation of the site, midday relative humidity, and average daily windspeed at the stream surface. The latitude and longitude of the site should be entered to the nearest .1 degree. The longitude of the center of the local time zone can be found in Table 1 and is entered to the nearest degree. Mean site elevation is entered in meters. The relative humidity (%) should approximate the humidity at 1300 hours local standard time and is entered to the nearest 1%. Average windspeed may be entered to the nearest .01 m s^{-1}.

READ LAT, LONG, LONGZ, IDST, MMDD, ELEV, HUMID, WINDSP
FORMAT (2F5.1, 3I5, 2F5.0, F5.2)

COLUMNS	DESCRIPTION
1-5	Enter the latitude of the site. Format - F5.1.
6-10	Enter the longitude of the site (assumed to be west). Format - F5.1.
11-15	Enter the longitude of the center of the local time zone (from Table 1). Format - I5.
16-20	The model assumes daylight savings time is in effect for the desired date. If this is not the case enter any number greater than zero. Format - I5.

Time Zone	Longitude at Center	Representative Cities
Eastern	75°	Camden, New Jersey
Central	90°	Memphis, Tennessee
Mountain	105°	Denver, Colorado
Pacific	120°	South Lake Tahoe, California

Table 1. Longitude at the center of time zones.

21-25	Enter the desired simulation date in MMDD format (e.g., Sept. 10 would be entered as 0910). Format - I5.
26-30	Enter the mean elevation of the site. Format - F5.0.
31-35	Enter midday relative humidity. Format - F5.0.
36-40	Enter mean daily windspeed. Format - F5.2.

Site default options record. Included in the default options record are the site default groundwater seepage ($\ell\ s^{-1}$ per 100 m of channel), the average daily temperature of the groundwater (°C), and an indicator for site default air temperatures.

The model keys on the values of the input groundwater seepage and temperature to determine if default values were specified. If the groundwater seepage value is not equal to zero, then the input value becomes the site default. Similarly, if the groundwater temperature value is greater than zero, then the input value becomes the site default. Groundwater seepage may be positive, indicating a flow of groundwater into the stream, or negative, indicating a loss of water by the stream. Groundwater temperature is only relevant if the seepage is positive.

The value of the site default air temperature indicator establishes whether or not default values are supplied and, if so, in what form they are presented. Table 2 (Section 3.3.2) presents the allowable values and their meanings for the site default air temperature indicator.

```
READ     SITGWQ, SITGWT, IOBS
FORMAT (F5.2, F5.1, I5)
```

COLUMNS	DESCRIPTION
1-5	Enter a site default value for groundwater seepage. Leave these columns blank (or enter 0) if no site default value is desired. Format - F5.2.
6-10	Enter a site default value for groundwater temperature. Leave these columns blank (or enter 0) if no site default value is desired. Format - F5.1.
11-15	Enter an appropriate indicator value from Table 2 for site default air temperatures (leaving the field blank is equivalent to entering 0). Format - I5.

Site default air temperature records. If you indicated that you want to input site default air temperature values (i.e., you entered a number other than 0 in columns 11-15 of the default options record), you must include one or more site default air temperature records. These records are free field and have the same requirements as the section air temperature record. Refer to Section 3.3.2 and input the appropriate records.

Site output options record. This record contains a field to enter the number of sets of section data records, an indicator to generate a printer plot of the stream sections, the size of this plot, an indicator to generate a table of solar altitude and azimuths for the site on the indicated simulation date, and an area for more identification remarks that appear in the header on each page of output.

READ TSEC, PLTSEC, ROWS, COLMNS, TBLALZ, TITLE2
FORMAT (I2, A1, 2I3, A1, A70)

COLUMNS	DESCRIPTION
1-2	Enter the number of sets of section data records (i.e., the number of identified stream sections you are processing) for this site. Format - I2.
3	Enter "Y" if you want a printer plot of the stream sections. Enter "N" (or leave blank) if you don't. Format - A1.
4-9	If you entered "Y" in column 3 and you want a plot size other than 50 rows by 50 columns, enter the number of rows for the plot in columns 4-6 (max is 104) and the number of columns for the plot in columns 7-9 (max is 100). Format - 2I3.
10	Enter "Y" if you want a table of solar altitudes and azimuths. Enter "N" (or leave blank) if you don't. Format - A1.

11-80	Enter up to 70 characters of identifying information for this site. The first 40 characters are included in output page headers. Format - A70.

3.3.2 Section Data Records

A set of section data consists of at least 6 records--a section identifier record, a stream characteristics record, 2 shading characteristics records, a section input options record, and a section output options record. In addition, one or more records may be required to supply each of section air temperature values, section inflow and inflow temperature values, and tributary flow and temperature values.

There must be one set of section data records for each stream section to be processed. At least one set must be for a stream section that has been identified as a headwater section.

Remember, stream aspects are measured in degrees clockwise from north to an imaginary vector directed downstream. The right and left hand sides of the stream channel are to the observers right and left as he faces downstream. Southeast is defined to be from due north to 30° east of due south, southwest is from due north to 30° west of due south, and south is from 30° east to 30° west of due south.

Section identification record. The section identification record contains the stream section's upstream and downstream node identifiers, a section number, and a field for identifying comments.

Again, node identifiers consist of one or two characters that identify the node and enable the model to properly link the stream sections. Each headwater section must have an upstream node ID of "HW". All other node ID's must be unique. The model does not distinguish between leading and trailing blanks. That is, the node ID " A" is the same as "A ". The section number and comments are for further identification.

READ NODES, SECNUM, SECOM
FORMAT (A4, 1X, I5, A70)

COLUMNS	DESCRIPTION
1-4	Enter the upstream node ID in columns 1-2 and the downstream node ID in columns 3-4. Format - A4.
6-10	Enter a section number. Format - I5.
11-80	Enter up to 70 characters of identifying information for this section. Format - A70.

Stream characteristics record. This record includes the stream aspect in degrees, the stream gradient (%), the section length (m), the average section width (m), the velocity of the water through the section (m s^{-1}), and the percent of the stream section that (1) is less than 20 cm deep, and (2) has bed materials comprised of bedrock or non-protruding boulders greater than 25 cm in diameter. The stream width estimate should exclude stagnant pools and protruding boulders. This record is free field format.

READ NSTAZ, GRAD, SECLEN, WIDTH, VEL, PERDB

COLUMNS	DESCRIPTION
1-80	Enter the stream aspect. Format - free field integer.
	Enter the stream gradient. Format - free field floating point.
	Enter the section length. Format - free field floating point.
	Enter the stream width. Format - free field floating point.
	Enter the water velocity. Format - free field floating point.
	Enter the percent of the stream section where water depth is less than 20 cm and the bed consists of bedrock or boulders greater than 25 cm in diameter. Format - free field floating point.

Shading characteristics records. The shading characteristics of the stream section are presented in two records. The first consists of the topographic and forest shade angles in degrees to the southeast, south, and southwest, and the hillslope and forest shade angles on both sides of the stream channel measured in degrees perpendicular to the longitudinal axis of the stream. This record is free field format.

READ (TOPSHA(I), I=1,3), (HSA(I), I=1,2), (FORSHA(I), I=1,3),
(PFORSH(I), I=1,2)

COLUMNS	DESCRIPTION
1-80	Enter the topographic shade angles, first to the southeast, then south, and then southwest. Format - free field floating point.
	Enter the hillslope angles, first on the right side of the stream then the left side. Format - free field floating point.
	Enter the forest shade angles, first to the southeast, then south, then southwest. If there are no trees in a given direction then the forest shade angle should equal the

corresponding topographic shade angle. Format - free field floating point.

Enter the perpendicular forest shade angles, first on the right side and then the left side of the stream. If there are no trees on a given side then the perpendicular forest shade angle should equal the corresponding hillslope angle. Format - free field floating point.

The second shading characteristics record consists of canopy cover coefficients for both sides of the stream, height of the forest vegetation (tree height) on each side of the stream, the buffer strip width for both sides of the stream, and the percent of the stream section that is provided direct, continuous shading by overhanging brush and logs. Canopy cover coefficients are decimal fractions between 0 and 1 inclusive and may be to the nearest .01. Tree height is entered to the nearest meter. Buffer strip widths are entered in meters. (See Section 4.3 for a discussion of buffer strips.) This record is free field format.

READ (CC(I), I=1,2), (H(I), I=1,2), (BW(I), I=1,2), PBRUSH

COLUMNS	DESCRIPTION
1-80	Enter a canopy cover coefficient for the right side and then the left side of the stream channel. If there are no trees enter 0. Format - free field floating point. Enter the average tree height for the right side and then the left side of the stream channel. If there are no trees enter 0. Format - free field floating point. Enter the buffer strip width for the right side and then the left side of the stream channel. If the forest is considered continuous (see Section 4.3) enter -1 for the buffer width. If there are no trees enter 0. Format - free field floating point. Enter the percent of the stream section that is provided direct, continuous shading by overhanging brush and logs. Format - free field floating point.

Section input options record. This record contains values to indicate if section air temperatures are input, if section inflow and inflow temperatures are input, and if flow and temperatures from a tributary are input. Each indicator establishes whether or not values were input for the corresponding parameter and, if so, in what form they are presented. The possible values for each indicator and their meaning are presented in Table 2. If the air temperature indicator is 0 then the model will use the site default air

Value	For Parameter	Means
0	Air temperatures Inflow temperatures Tributary temperatures	No values input
1	Inflow temperatures Tributary temperatures	Input 1 value representing the average daily temperature
2	Air temperatures	Input daily maximum and minimum air temperature
24	Air temperatures Inflow temperatures Tributary temperatures	Input 24 successive values in 1 hour intervals beginning at 0100 hours
48	Air temperatures Inflow temperatures Tributary temperatures	Input 48 successive values in 30 minute intervals beginning at 0030 hours
96	Air temperatures Inflow temperatures Tributary temperatures	Input 96 successive values in 15 minute intervals beginning at 0015 hours

Table 2. Possible values and meanings of input indicators for section or site default air temperatures, section inflow temperatures, and section tributary temperatures.

temperature values. A value of 2 is valid only for air temperatures. If you enter a value other than 0 for the inflow and tributary indicators you must supply a flow value and a corresponding number of temperatures. If the value of the inflow indicator is 0, the model will use the outflow and outflow temperatures of the immediate upstream section(s) as input to this section. Note that you must input inflow and inflow temperatures if this is a headwater section. Also included in this record is an indicator to determine if groundwater seepage is a factor for this stream section and two fields to enter groundwater seepage and groundwater temperature. If the value of the indicator is greater than zero then groundwater is a factor. If groundwater is a factor then you can enter the groundwater seepage ($\ell\ s^{-1}$ per 100 meters of channel) in the appropriate field, or, if you leave the field blank, the model will use the site default groundwater seepage. Similarly, if groundwater is a factor and groundwater seepage is positive, indicating seepage into the stream section, you can enter the groundwater temperature (°C) in the appropriate field, or, if you leave the field blank, the model will use the site default groundwater temperature.

READ IOBSAT, IOBSIF, IOBSTB, GWFLAG, GWSEEP, GWTEMP
FORMAT (5X, 4I5, F5.2, F5.1)

COLUMNS	DESCRIPTION
5-10	Enter the section air temperature indicator (Table 2). Note: blanks are equivalent to entering zero. Format - I5.
11-15	Enter the section inflow indicator (Table 2). Format - I5.
16-20	Enter the section tributary flow indicator (Table 2). Format - I5.
21-25	Enter a number greater than zero if groundwater is a factor for this section, otherwise leave blank. Format - I5.
26-30	If groundwater is a factor and you do not want to use the site default seepage value, enter the groundwater seepage. If you do want to use the site default value, leave this field blank. Format - F5.2.
31-35	If groundwater is a factor and groundwater seepage is positive then if you do not want to use the site default temperature value, enter groundwater temperature. If you do want to use the site default value, leave this field blank.

Section air temperature record. This record must be included if the air temperature indicator (columns 5-10 of the section input options record) is other than zero or blanks. If the air temperature indicator is 2 then enter the daily maximum and then the daily minimum air temperature to the nearest .1 °C. If the air temperature indicator is greater than 2 then enter the appropriate number of air temperature values. These records are free field format.

Section inflow and inflow temperature records. These records must be included if the section inflow indicator (columns 11-15 of the section input options record) is other than zero or blanks. Enter the section inflow to the nearest .01 $\ell\ s^{-1}$ and the appropriate number of inflow temperature values to the nearest .1 °C. These records are free field format. Remember, this record must be included for headwater sections.

Tributary flow and temperature records. These records must be included if the tributary flow indicator (columns 16-20 of the section input options record) is other than zero or blanks. Enter the tributary flow to the nearest .01 $\ell\ s^{-1}$ and the appropriate number of tributary temperature values to the nearest .1 °C. These records are free field format.

Section output options record. This record contains output options indicators. These indicators are used to either select or suppress the output options described in Section 3.2.

```
READ    (SECTIO(I), I=1,7), IDEST
FORMAT (7A1,I1)
```

COLUMNS	DESCRIPTION
1	Enter "Y" if you want the section input echoed. Enter "N" or leave blank if you do not. Format - A1.
2	Enter "Y" if you want a table of section input and output temperatures. Enter "N" or leave blank if you do not. Format - A1.
3	If you entered "Y" in column 2 then enter 1 for the table to be in one hour intervals, 2 for 30 minute intervals, or 3 for 15 minute intervals. Format - A1.
4	If you entered "Y" in column 2 and you want to include the energy budget components in the table then enter "Y". If you do not, enter "N". Format - A1.
5	Enter the appropriate indicator for plots of the section input and output temperatures: 0 (or blank) for no plot, 1 for printer plots, 2 for Calcomp plots, or 3 for both printer and Calcomp plots. Format - A1.
6	Enter the appropriate indicator for plots of the change in temperature: 0 (or blank) for no plot, 1 for printer plots, 2 for Calcomp plots, or 3 for both printer and Calcomp plots. Format - A1.
7	If you elected to generate a printer plot (i.e., you entered a 1 or 3 in columns 5 and/or 6), enter an appropriate plot size indicator: 1 for a 41 row by 73 column plot, or 2 for a 56 row by 97 column plot. Format - A1.
8	If you elected to generate a Calcomp plot (i.e., you entered a 2 or 3 in columns 5 and/or 6), enter a plotfile format destination indicator (see Section 3.5): 0 for mass storage unit 7, 1 for punched/PUNCH$, 2 for ANSI tape unit 9. Format - I1.

3.4 Data Set Structure

Your completed data set should be structured like this:

Site data records:	Identifier
	Site characteristics
	Site default options
	[Site default air temperatures]
	Output options
First section data records:	Identifier
	Stream characteristics
	Shading characteristics
	Shading characteristics
	Input options
	[Air temperatures]
	[Inflow and temperatures]
	[Tributary flow and temperatures]
	Output options
Second section data records:	Identifier
	•
	•
	•
	Output options
•	
•	
•	

Those records enclosed in brackets may or may not be present in the data set.

If you have more than one site to perform temperature simulations for, data for the next site can be included immediately following the end of the last data record of the previous site.

3.5 Model Execution

The TEMP-84 MODEL resides on the UNIVAC 1100/84 at the FCCC. The model is located in WSDG's permanent program file WSDU*WATER. Model execution is accomplished by issuing the ECL commands:

```
@XQT WSDU*WATER.TEMP-84
@ADD,P YOUR*DATAFILE.
```

or

```
@ADD,P YOUR*DATA.ELEMENT
```

where YOUR*DATAFILE or YOUR*DATA.ELEMENT (just example names) contains the required data.

If you elected to generate Calcomp plots, the plotfile (i.e., the file containing the plotter instructions) may be written to a mass storage data file--used for sending plots to a DATA 100 Remote Job Entry station (RJE), punched as 80 column records--used for sending plots to a Harris RJE, or written to an ANSI formatted 1600 BPI 9 track unlabeled

magnetic tape--used for plotting on the FCCC's Calcomp plotter located in Fort Collins. Plotfiles written to mass storage are directed by the model to logical unit 7. Punched plotfiles are directed to the system file PUNCH$. Output written to magnetic tape is directed to logical unit 9.

If you are generating Calcomp plots, you must issue one of the following commands prior to issuing the @XQT command:

```
(1)   @USE 7.,YOUR*PLOTFILE.                (mass storage)
(2)   @BRKPT PUNCH$/YOUR*PLOTFILE.          (punched output)
(3)   @USE 9.,YOUR*PLOTFILE.                (magnetic tape)
```

where YOUR*PLOTFILE is the name (just an example) of the data file (if (1) or (2)) or tape (if (3)) that is to contain the output plotfile.

The TEMP-84 MODEL creates a temporary scratch file equated to logical unit 8. Therefore, unit 8 cannot be assigned to your run or the program will abort. This can be ensured by issuing the command:

```
@FREE  8.
```

prior to issuing the @XQT command.

3.6 Example Input and Output

To demonstrate the model's input and output, an example data set was created (Figure 11). The data set was constructed to demonstrate all input and output options and corresponds to the stream system depicted in Figure 12. This data set resides in the element TEMP84 of WSDG's program file WSDU*SAM. As an aid to understanding the model's input and output it is suggested that you execute TEMP-84 using this data as input and then carefully review the resultant output.

The following runstream can be used to execute the example and list the input data:

```
@FREE  8.
@XQT  WSDU*WATER.TEMP-84
@ADD,P  WSDU*SAM.TEMP84
@PRT,S  WSDU*SAM.TEMP84
```

```
EXAMPLE DATASET FOR THE EXECUTION OF TEMP-84
  380 1180  120       0827 2100   40  100
  100   70   48
    5.7  5.4  5.5  5.7  5.3  5.8  5.5  5.6  4.7  4.8  4.6  4.6
    5.0  5.6  6.2  8.9 12.9 15.7 24.7 26.5 26.8 24.9 21.1 21.8
   25.6 22.9 20.5 19.8 19.8 19.3 17.5 16.2 12.8 12.1 11.1 10.3
    9.8  9.4  9.0  8.3  7.3  7.0  7.5  6.5  6.3  6.3  6.4  6.5
 9Y 60100Y 40 COLUMNS FOR A PAGE HEADER TO APPEAR HERE
HW A     1 HW -> A   PROPOSED HARVEST - SUPPLIED INFLOW & AIR TEMPS
       120    8  500    1  .25  100
         1   11   18   23   23        17   11   18   23   64
         0  .55         0   46         0   -1        50
         2   96    0    1   .4   7.
      28.0  5.0
      31.0  7.9  7.9  7.8  7.8  7.7  7.7  7.6  7.6  7.5  7.5  7.5  7.4
            7.4  7.4  7.3  7.3  7.2  7.2  7.1  7.1  7.1  7.0  7.0  6.9
            6.9  6.9  6.9  6.9  6.9  6.9  6.9  7.0  7.2  7.3  7.4  7.6
            7.8  8.1  8.3  8.6  9.0  9.3  9.6 10.0 10.3 10.5 10.8 11.0
           11.3 11.7 12.0 12.2 12.2 12.2 12.2 12.2 12.2 12.2 12.0 11.9
           11.9 11.8 11.7 11.6 11.5 11.4 11.3 11.2 11.1 10.9 10.8 10.6
           10.5 10.3 10.2 10.1  9.9  9.8  9.7  9.6  9.4  9.3  9.2  9.1
            9.0  8.9  8.8  8.7  8.6  8.5  8.5  8.4  8.3  8.3  8.2  8.2
YY3Y112
 A B     2 A -> B - INFLOW FROM UPSTREAM - SITE DFLT AIR TEMPS
       120    8  250    1  .25   90
         2   13   19   24   24        12   46   62   70   70
       .70  .55         48   38        -1   -1        25
         0    0    0    1   .4   7.
YY1N111
HW C     3 HW -> C PROPOSED HARVEST WITH BUFFER -SUPPLIED INFLOW & AIR TEMPS
       220   10  600   .5  .25  100
         5   15   20   22   24        12   40   50   65   70
        .6   .6         44   40        -1   20        20
         2    1    0    1    0    0
      28.0  5.0
      10.0  7.0
YY2Y112
 C D     4 C -> D - INFLOW FROM UPSTREAM - SITE DFLT AIR TEMPS & GW
       220   10  100   .5  .25  100
         5   15   20   22   24        12   40   50   65   70
       .60  .60         44   40        -1   -1        20
         0    0    0    1    0    0
YY3N111
 D E     5 D -> E  CONFLUENCE WITH TRIBUTARY AT D
       220    8   50    1  .25  100
         5   15   20   22   24        12   40   50   65   70
        .6   .6         44   40        -1   -1        20
         0    0   24    1    0    0
       6.0  8.8  8.6  8.4  8.3  8.1  7.9  7.9  8.0  8.6  9.6 11.0 12.0
           13.2 13.2 12.9 12.6 12.2 11.6 11.1 10.6 10.1  9.7  9.4  9.2
YY1N111
 E F     6 E -> F - ALONG ROAD -INFLOW UPSTREAM - SITE DFLT AIR TEMPS & GW
       200    6  400  1.5   .2  100
         5   15   20   20   10        10   20   40   50   30
       .60  .60         48   40        -1   -1        30
         0    0    0    1    0    0
YY1N111
 F B     7 F -> B - INFLOW FROM UPSTREAM - SITE DFLT AIR TEMPS & GW
       200    8  250 1.25   .2   90
         5   15   20   20   10        15   40   50   65   70
       .80  .60         44   40        -1   -1        30
         0    0    0    1    0    0
YY1N111
 B G     8 B -> G - CONFLUENCE AT B
       170    8  600 1.75   .1   10
         9   19   25   29   18        60   60   70   70   75
       .60  .70         40   42        -1   -1        20
         0    0    0    0    0    0
YY2Y111
 G H     9 G -> H
       190    6  500  1.4  .15   40
        10   20   25   25   10        65   65   60   70   70
       .75  .75         40   40        -1   -1        25
         0    0    0    0    0    0
YY1Y112
```

Figure 11. Example data set located in WSDU*SAM.TEMP84.

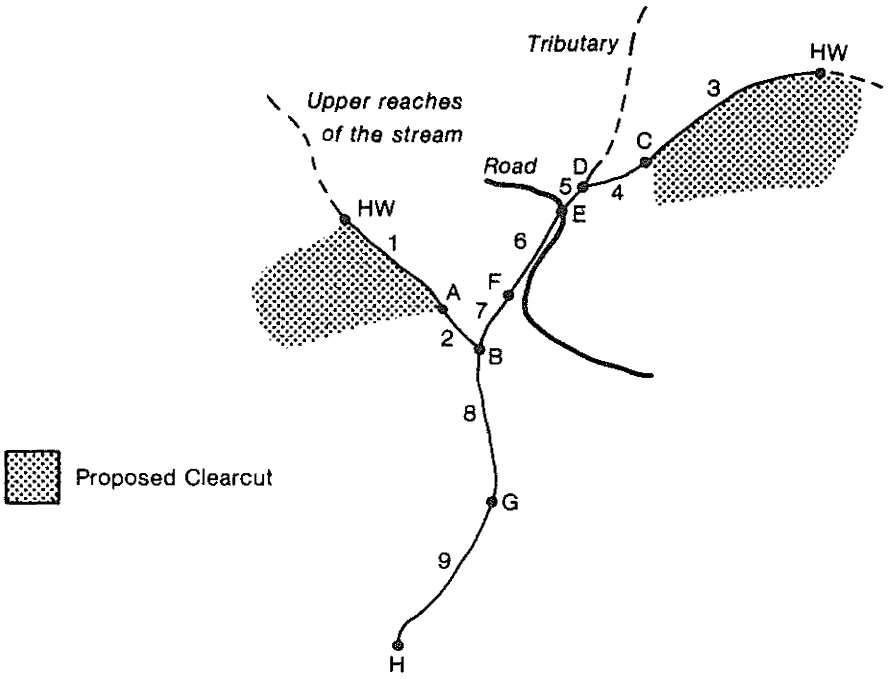


Figure 12. Stream system corresponding to the example data in Figure 11.

4.0 MODELING PROCEDURES AND EQUATIONS

To simulate stream temperatures for each section of a stream system, the sections are processed (i.e., stream temperatures calculated) one at a time in a particular order. This order ensures that each section is processed only after all sections upstream from it have been processed. The order is determined in this way. A stream section is selected as a candidate for processing (initially, the first headwater section encountered in the input data becomes the first candidate). If the candidate is a headwater section it has no upstream sections and is immediately processed. If the candidate is not a headwater section then its immediate upstream sections are examined to determine if they have all been processed. If so, the candidate section is processed and the section immediately downstream becomes the next candidate. If there are one or more sections immediately upstream that have not been processed, one of the unprocessed sections is selected as the candidate. The new candidate's upstream sections are examined and again, the candidate is either processed and the immediate downstream section becomes the next candidate, or a new candidate is chosen from the immediate upstream sections.

The steps and equations involved in simulating the stream temperatures for the stream sections are presented in Sections 4.1 and 4.2. Supporting miscellaneous computations and equations are presented in Sections 4.3 through 4.7.

4.1 Partitioning the Stream Sections

When a stream section has been selected for processing, it is first partitioned into sub-sections. A minimal number of sub-sections are formed with each sub-section being of equal length and flow time with the flow time being less than or equal to 15 minutes.

The day is divided into 96 time intervals with each time interval beginning 15 minutes later than the previous one and each equal in length to the sub-section's flow time. The simulation begins with the uppermost sub-section with its input temperatures being the output temperatures of the section immediately upstream corresponding to the appropriate time intervals. It's beginning time interval is the time nearest to but past 2400 hours of the output time of the immediate upstream section. If more than one section lies immediately upstream, then the beginning input time corresponds to the time nearest to but past 2400 hours of the output time of that immediate upstream section that was processed first. If the inflow temperatures were user supplied, the beginning input time is 0015 hours.

Temperature calculations are then performed for each of the 96 time intervals for the uppermost sub-section. Net heat gain or loss is added to the sub-section's input temperatures to form the output temperatures. These output temperatures then become the input temperatures of the next downstream sub-section.

By way of an example, suppose the section to be processed was 600 m long with an average water velocity of .10 m s^{-1}. The section flow time is 600/(.10•60) = 100 min. The section would be partitioned into 7 sub-sections, each with a flow time of 100/7 ≈ 14.3 minutes, and each of length 600/7 ≈ 85.7 m. Further, suppose the section immediately upstream was a headwater section with a flow time of 12 minutes. The input temperatures of the headwater section would be those at time 0015 hours, 0030 hours, 0045 hours, ... , 2400 hours and the output temperatures would be at times 0027 hours, 0042 hours, 0057 hours, ... , 2357 hours, 0012 hours (i.e., add 12 minutes to each input time). Thus, the input temperatures of the uppermost sub-section of the section to be processed would be at times 0012 hours, 0027 hours, 0042 hours, ..., 2357 hours and its output temperatures would be at times 0026.3 hours, 0041.3 hours, 0056.3 hours, ..., 0011.3 hours.

4.2 Energy Budget Components

To calculate the net heat gain or loss by the stream through a particular sub-section, the effects of each of net solar radiation, the storage and release of heat by bedrock, net longwave radiation, evaporative and convective heat flux, and the heat advected into the stream by groundwater is evaluated for each of the 96 time intervals. For each component, positive values indicate energy available to the stream. Negative values indicate an energy loss. To approximate an average, the solar parameters time (i.e., hour angle), altitude, and azimuth are calculated for the middle of the time interval in question.

4.2.1 Net Solar Radiation (HS)

Atmospheric effects. Once the sun rises above the theoretical horizon (a horizontal plane extended outward from the stream section), potential solar radiation is routed through the atmosphere. The flux of direct beam solar radiation available above the canopy, DIRHS, is computed by

$$DIRHS = S\ ATR^{M} \cos Z' \qquad (2)$$

where: S is the solar constant
= 0.033 ly s^{-1} (Rosenburg, 1974)
ATR is the atmospheric transmissivity coefficient
= 0.78 (Reifsnyder and Lull, 1965; p. 21)
M is the optical air mass thickness at the elevation of the site (atmospheres)
Z' is the apparent zenith angle (Equation (73)).

The optical air mass thickness is given by

$$M = M_o\ RP \ . \qquad (3)$$

RP is the ratio of air pressure at the stream elevation to the air pressure at sea level (List, 1966; p. 268), and M_o is the optical air mass thickness at sea level. The ratio RP is dependant upon the elevation of the site, E (m):

$$RP = \left(\frac{288 - 0.0065\ E}{288} \right)^{5.256} . \qquad (4)$$

From Robinson (1966) the value of M_o (see Appendix A) is

$$M_o = \frac{1}{\cos Z} = \frac{1}{\sin ALT} \tag{5}$$

where Z is the zenith angle (Equation (72)) and ALT is the solar altitude (Equation (70)). The optical air mass thickness for stream sections above sea level is reduced by RP to account for reduced atmospheric absorption of solar radiation (Campbell, 1977).

The diffuse beam solar radiation available immediately above the canopy is calculated as a fraction of the direct beam radiation incident upon a horizontal plane. The direct beam component, DIRHOR is

$$DIRHOR = S\ ATR^{M} \cos Z \ . \tag{6}$$

The diffuse beam solar radiation available above the canopy, DIFHS, is given by

$$DIFHS = RD \bullet DIRHOR \tag{7}$$

where RD is the ratio of diffuse to direct beam radiation on a horizontal surface (see Appendix A). The ratio RD was developed from data for "standard cloudless atmosphere" (Brooks, 1959) in Reifsnyder and Lull (1965):

$$RD = 0.0167 + 0.1072 \left(\frac{1}{\cos Z} \right) \ . \tag{8}$$

Topographic effects. Field estimates of the average topographic shading angles to the southeast, south, and southwest are used to determine the effects of topographic shading on the direct beam component of solar radiation. The direct beam solar radiation flux remains zero whenever the solar altitude (ALT) is less than or equal to the topographic shade angle (A) shown in Figure 2 (i.e., DIRHS = 0 when ALT $\leq$ A). The angle A is equal to the topographic shade angle to the southeast, south, or southwest depending upon the position of the sun. If AZ (the solar azimuth measured clockwise from north) is such that $0° < AZ < 150°$ then the sun is said to be in the southeast and the angle A is equal to the topographic shade angle to the southeast. Similarly, if $150° \leq AZ \leq 210°$ the sun is in the south, and if $210° < AZ \leq 360°$ the sun is in the southwest and the appropriate topographic shade angles are selected. Note that it is assumed that the topographic shading angles measured for southerly azimuths are representative of those for northerly azimuths. Potential errors associated with this assumption should be minimal since the

sun can appear in northerly azimuths only in early morning or late afternoon periods. At these times the solar altitudes are relatively low and solar radiation is generally insignificant.

The flux of the diffuse beam component of the solar radiation is also affected by topographic shading. This effect is handled by calculating the diffuse beam radiation available below the forest canopy as the sum of diffuse radiation received from the opening in the forest canopy directly above the stream and that portion of the diffuse radiation assumed to pass through the forest canopy. In this way that portion of diffuse radiation blocked by topographic shading (determined by the hillslope angles) on the right and left sides of the channel is omitted.

Forest canopy effects. As for topographic shading, three angle estimates are required for evaluating the effects of forest canopy shading for direct beam radiation. These angles represent field estimates of the angle from the stream to the canopy top (angle B in Figure 2) to the southeast, south, and southwest. For a given solar azimuth, an appropriate forest shading angle B is chosen. If the sun is above the forest shade angle (i.e., ALT $\geq$ B), then the amount of direct beam radiation available below the canopy is DIRHS (Equation (2)). However, if the solar altitude is such that A < ALT < B (where A is the appropriate topographic shade angle), then the direct beam radiation needs to be routed through the forest canopy.

It is assumed that the amount of direct beam radiation attenuated by the forest canopy is a function of the canopy cover coefficient and the length of the direct beam's path through the canopy. Path lengths are discussed in Section 4.3. The flux of direct beam solar radiation available below the forest canopy, DIRHS2, is

$$\text{DIRHS2} = \text{DIRHS}\ TC^{AVEPL} \qquad \text{if } A < ALT < B \qquad (9)$$

or

$$\text{DIRHS2} = \text{DIRHS} \qquad \text{if } ALT \geq B \qquad (10)$$

where TC is the canopy transmissivity coefficient and AVEPL is the average path length of the direct beam through the forest canopy (Equation (62)). The canopy transmissivity coefficient is given by

$$TC = 1 - 0.9\ CC \qquad (11)$$

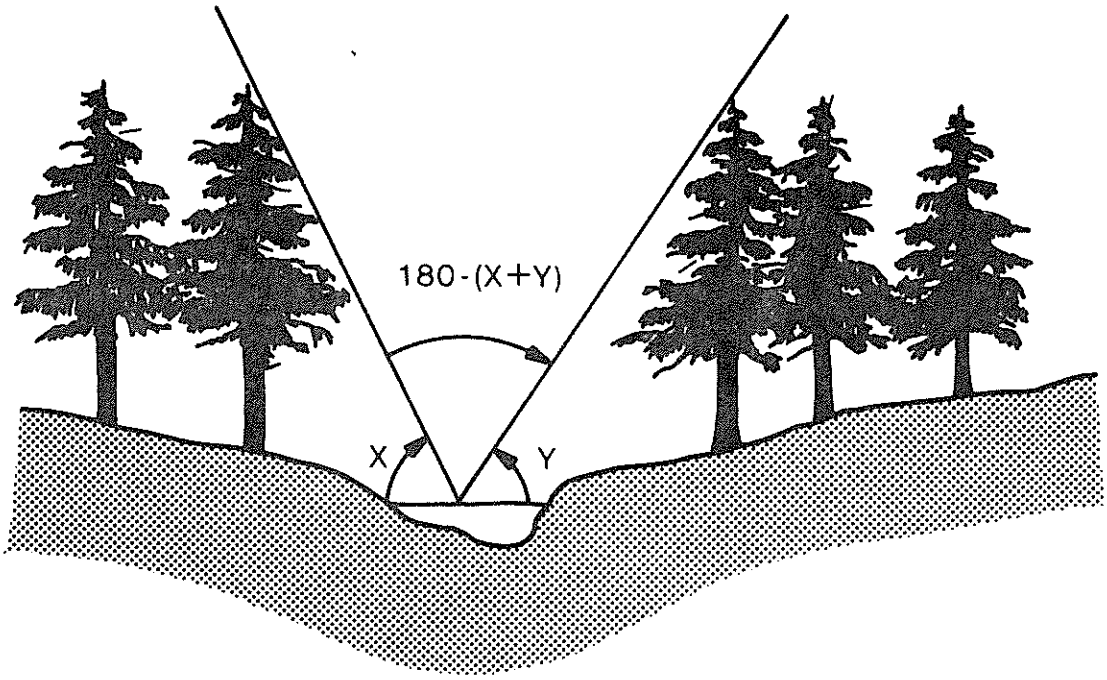


Figure 13. Canopy angles used for routing diffuse solar and longwave radiation to the stream.

where CC is the canopy cover coefficient for the appropriate side of the channel ($0 \leq CC \leq 1$).

The diffuse beam radiation available below the forest canopy is the sum of the diffuse beam radiation received from an opening in the canopy directly above the stream and the amount of diffuse beam that passes through the canopy. The diffuse beam flux from the canopy opening, DIFHSKY, is

$$\text{DIFHSKY} = \left(\frac{180 - (X + Y)}{180}\right) \text{DIFHS} \tag{12}$$

where X and Y are field estimates of the forest shade angles on the right and left sides of the channel measured perpendicular to the longitudinal axis of the stream (Figure 13).

The amount of diffuse beam passing through the canopy on the X side, DIFHSX, and the Y side, DIFHSY, of the channel is

$$\text{DIFHSX} = \left(\frac{X - HSX}{180}\right) \text{DIFHS TC}^{\text{AVEPLX}} \tag{13}$$

$$\text{DIFHSY} = \left(\frac{Y - HSY}{180}\right) \text{DIFHS TC}^{\text{AVEPLY}} \tag{14}$$

where HSX and HSY are the hillslope angles on the X and Y sides of the channel and AVEPLX and AVEPLY are the average path lengths of the diffuse radiation through the canopy on the X and Y sides of the channel. Note that the terms (X - HSX)/180 and (Y - HSY)/180 in Equations (13) and (14) effectively eliminate that portion of DIRHS that is blocked by the hillslopes on both sides of the channel.

The total diffuse beam flux available immediately below the canopy, DIFHS2, is

$$DIFHS2 = DIFHSKY + DIFHSX + DIFHSY \quad . \tag{15}$$

Overhanging brush and logs. After both direct and diffuse solar radiation has been routed through the forest canopy, shading effects of brush and logs overhanging the water surface are calculated:

$$DIRHS3 = DIRHS2 \, (\, 1 - BRUSH \,) \tag{16}$$

$$DIFHS3 = DIFHS2 \, (\, 1 - BRUSH \,) \tag{17}$$

where BRUSH is the proportion of the stream surface shaded by overhanging brush and logs.

Thus far the potential solar radiation has been routed through the atmosphere, topography, forest canopy, and overhanging brush and logs. DIRHS3 and DIFHS3 represent the shortwave radiant energy fluxes available at the stream surface.

Air-water interface. Based on data in Sellers (1965), relationships between the albedo of moving water (i.e., the reflectivity of water to shortwave solar radiation) and the apparent zenith angle were developed (Appendix B):

$$REFL = 0.091\left(\frac{1}{\cos Z'}\right) - 0.0386 \qquad \text{if } 0° \leq Z' \leq 80° \tag{18}$$

or

$$REFL = 0.0515\, Z' - 3.635 \qquad \text{if } 80° < Z' \leq 90° \tag{19}$$

where REFL is the albedo (reflectivity) of the water surface.

The flux of direct beam radiation into the water, DIRHS4, is then determined by

$$DIRHS4 = DIRHS3 \, (\, 1 - REFL \,) \quad . \tag{20}$$

Lee (1978) indicates that for isotropic diffuse radiation, the flux (S_d) for a circular opening in a forest canopy can be determined from

$$S_d = S_{d'} \cos^2 i \ .$$

$S_{d'}$ is the diffuse radiation on a horizontal surface without vegetative shading and i is the angle from a horizontal surface to the top of the canopy in a circular forest opening. Evaluating this equation for i = 45° yields $S_d = \frac{1}{2} S_{d'}$. Thus, it is assumed that one-half of the diffuse radiation originates above a 45° angle and one-half below. In the TEMP-84 MODEL, an effective zenith angle of 45° is used in routing the diffuse beam radiation in the stream. Evaluating Equation (18) for an effective zenith angle of 45° yields REFL = 0.09. The diffuse beam radiation flux entering the stream, DIFHS4, is

$$\text{DIFHS4} = 0.91 \ \text{DIFHS3} \ . \qquad (21)$$

Transmitting the flux through the water. For pure water, Sellers (1965) indicates that approximately 50% of the solar energy that passes the air-water interface reaches a depth of 10 cm. Whether the solar radiation is transmitted to the stream bottom or absorbed by the water depends primarily upon the depth of water and the zenith angle of the incoming solar radiation. The flux of energy at the stream bottom is calculated as follows.

The average depth of the stream (cm) is

$$\text{DEPTH} = \text{FLOW VEL}^{-1} \text{WIDTH}^{-1} \text{K} \qquad (22)$$

where:

FLOW	is the average flow of the sub-section in $\ell\ s^{-1}$ (equal to the sub-section's inflow plus one-half of the total groundwater seepage ($\ell\ s^{-1}$) for the sub-section)
VEL	is the average water velocity through the sub-section ($m\ s^{-1}$)
WIDTH	is the average width of the sub-section (m)
K	= (100 cm/1 m) (1 m^3/1000 ℓ).

The travel distance of solar radiation in water, H (cm), is

$$H = \frac{\text{DEPTH}}{\cos R} \qquad (23)$$

where

$$R = \sin^{-1}\left(\frac{\sin Z}{n}\right) \tag{24}$$

with n being the index of refraction for water (n= 1.333). Equation (23) was developed from data presented by Jerlov (1976). Equation (24) is presented in Williams (1970) and in Austin and Halikas (1976). The proportion of direct beam solar energy transmitted through the water, TRW, is now calculated by

$$TRW = 0.415 - 0.194 \log_{10}(H) \ . \tag{25}$$

DIRHS5, the flux of direct beam radiation at the stream bottom is given by

$$DIRHS5 = DIRHS4 \cdot TRW \ . \tag{26}$$

Similarly, assuming an effective zenith angle of 45° (i.e., Z=45° in Equation (24)), the flux of diffuse beam radiation at the stream bottom is

$$DIFHS5 = DIFHS4 \cdot TRW \ . \tag{27}$$

Water-stream bed interface. Solar energy reaching the stream bed can be reflected back into the water or absorbed by the bed material. Utilizing data from Sellers (1965), the reflectivity of rock materials (REFLR) as a function of zenith angle was developed (Appendix C):

$$REFLR = \exp[\ 0.0214\ Z' - 1.941\ ] \ . \tag{28}$$

The flux of solar energy absorbed by the bed material is determined by

$$DIRHS6 = DIRHS5\ (\ 1-REFLR\ ) \tag{29}$$

$$DIFHS6 = DIFHS5\ (\ 1-REFLR\ ) \tag{30}$$
$$= 0.62\ DIFHS5 \qquad (\text{for } Z' = 45°) \ .$$

Because the solar energy is absorbed by the bedrock at the rock-water interface, some of this energy may be conducted/convected directly to the stream. Sellers (1965, p. 139)

indicates that the partitioning of energy between a water and rock interface can be approximated by the ratio (R) of the thermal properties of the two media:

$$R = \frac{C_w K_w^{1/2}}{C_r K_r^{1/2}}$$

where: C_w is the heat capacity of water (1 cal cm^{-3} $°C^{-1}$)

K_w is the thermal diffusivity of water

$\approx$ 0.1 cm^2 s^{-1} for stirred water

$\approx$ 0.001 cm^2 s^{-1} for still water

$\approx$ 0.01 cm^2 s^{-1} (assumed value for moving water in a stream during low flow)

C_r is the heat capacity of bedrock

$\approx$ 0.53 cal cm^{-3} $°C^{-1}$ (0.46 to 0.60 for rock minerals)

K_r is the thermal diffusivity of bedrock

$\approx$ 0.045 (for quartz) .

Thus,

$$R \approx \frac{(1)(0.01)^{1/2}}{(0.53)(0.045)^{1/2}} \approx 0.9 \quad .$$

In other words, for every unit of energy absorbed by the bed material, approximately 0.9 units are absorbed by the water at the water-stream bed interface. As a result, the net solar radiation available to the stream, HS (ly s^{-1}), is calculated from the following:

$$HS = DIRHS4 + DIFHS4 - BDR\ (\ .53\ DIRHS6 + .53\ DIFHS6\ ) \qquad (31)$$

where BDR is that portion of the stream bed that has the properties that enable the bed materials to retain the absorbed energy (see below). Although this equation allows the computation of the net radiation flux, it should be noted that all of the energy "lost" to the stream bed is assumed to be recovered by the water via the conduction process discussed in the following section.

4.2.2 Heat Conducted to Bedrock (HB)

A portion of the solar radiation that reaches the water-stream bed interface is absorbed by the bed (Equations (29) and (30)). Of the amount absorbed by the bed, 47% (0.9/1.9) is conducted directly to the stream, and 53% (1.0/1.9) is stored by the bed. When the bed particles are small, the water surrounding the particles is efficient at recovering any absorbed radiant energy. Thus, it is assumed that only that portion of the bed that is made up of bedrock or boulders greater than 25 cm in diameter is able to retain the stored energy. The storage of energy by the remaining portion of the bed is considered negligible and that portion of the absorbed energy is returned directly to the water. Also, it is assumed that nearly all incoming solar radiation is absorbed within 20 cm of the surface and therefore, the composition of the bed does not influence stream temperatures if the water depth is greater than 20 cm. If BDR represents that portion of the stream where the bed is comprised of bedrock or boulders greater than 25 cm in diameter and the water depth is less than or equal to 20 cm, the radiant energy stored by the bed, HB (ly s^{-1}), is

$$HB = -BDR\ (\ .53\ DIRHS6 + .53\ DIFHS6\ ) \qquad (32)$$

(compare to Equation (31)).

It is assumed that this stored energy is retained until net shortwave radiation levels fall to one-half of the daily maximum. The stored energy is then released back to the stream uniformly over an 8-hour period. Also, since energy is being released, it is assumed none can be stored and so all energy reaching the stream bed during this release period is assumed to be absorbed by the water.

4.2.3 Longwave Radiation (HL)

The Stefan-Boltzmann radiation law forms the basis for estimating longwave radiation fluxes from the atmosphere, canopy, and water surface. This fundamental law of energy emission in equation form is

$$L = \varepsilon\sigma T^4$$

where:
- L is the longwave energy flux (ly s^{-1})
- ε is the emissivity of the body ($0 \leq \varepsilon \leq 1$)
- σ is the Stefan-Boltzmann constant ($\sigma = 1.355 \times 10^{-12}$ ly s^{-1} $°K^{-4}$)
- T is the surface temperature (°K) of the body.

Atmospheric longwave flux. Because of the complexity of determining effective emissivities and temperatures for a diffuse substance such as represented by the atmosphere, various empirical equations have been proposed for calculating longwave radiation from the atmosphere (Sellers, 1965). An improved equation for estimating longwave radiation from the atmosphere has been developed by Satterlund (1979) and is used in the TEMP-84 MODEL. The emissivity of the atmosphere, ε_a, is

$$\varepsilon_a = 1.08 \left(1 - \exp \left[-e_a^{\frac{T_a}{2016}} \right] \right) \tag{33}$$

where e_a is the atmospheric vapor pressure (Equation (66)), and T_a is the current air temperature (°K). The downward longwave radiant energy flux from clear skies, HLA, is

$$HLA = \varepsilon_a \sigma T_a^4 \ . \tag{34}$$

Equation (34) provides an estimate of the incoming atmospheric longwave radiation at the stream surface if no canopy shading or shading from brush and logs occur. When such shading exists, however, the incoming longwave must be routed (much like the shortwave radiation) through these materials. The flux of clear sky radiation from a canopy opening directly over the channel (HLA1) is determined by

$$HLA1 = \left(\frac{180 - (X + Y)}{180} \right) HLA \tag{35}$$

where X and Y are field estimates of forest shade angles as in Equation (12).

To determine the flux of atmospheric longwave radiation that is able to come directly through the canopy, an "effective" path length is determined using the procedures and canopy models for routing the diffuse beam components (Section 4.3). The atmospheric longwave fluxes from the X and Y sides of the channel, respectively, are

$$HLAX = \left(\frac{X - HSX}{180} \right) HLA \ TC^{\,AVEPLX} \tag{36}$$

and

$$HLAY = \left(\frac{Y - HSY}{180} \right) HLA \ TC^{\,AVEPLY} \tag{37}$$

(see Equations (13) and (14)). The total atmospheric longwave energy flux available directly above the channel, HLA2, is

$$HLA2 = HLA1 + HLAX + HLAY \quad . \tag{38}$$

Longwave flux from the canopy. The effective radiating surface of the canopy from the X and Y sides of the channel is calculated by

$$CSX = \frac{X}{180}\left(1 - TC^{AVEPLX} \right) \tag{39}$$

and

$$CSY = \frac{Y}{180}\left(1 - TC^{AVEPLY} \right) \tag{40}$$

(compare to Equations (36) and (37)). The additional downward longwave radiation from the canopy, HLC, is then

$$HLC = \left(CSX + CSY \right)\left(\varepsilon_c \sigma T_c^4 \right) \tag{41}$$

where ε_c is the emissivity of the canopy ($\varepsilon_c = 0.95$) and T_c is the temperature of the canopy (°K), assumed to equal the air temperature.

The total downward longwave flux (from the atmosphere and canopy) above the channel, HL, is

$$HL = HLA2 + HLC \quad . \tag{42}$$

This energy (HL) is routed through any overhanging brush or logs:

$$HL1 = HL\left(1 - BRUSH \right) + \varepsilon_b \sigma T_b^4 \left(BRUSH \right) \tag{43}$$

where BRUSH is as in Equations (16) and (17), ε_b is the emissivity of the brush and logs ($\varepsilon_b = 0.95$), and T_b is the temperature of the brush or logs (°K), assumed to equal the air temperature.

Longwave flux from the water. The longwave radiation emitted from the water, HLW, is determined by

$$HLW = \varepsilon_w \sigma T_w^4 \tag{44}$$

where ε_w is the emissivity of water ($\varepsilon_w = 0.97$) and T_w is the water temperature (°K). The water temperature is the temperature resulting from adding one-half of the sub-section's groundwater seepage to the sub-section's inflow and is calculated by Equation (63).

Net longwave flux. The net longwave radiation at the stream surface, HL2 (ly s^{-1}), is

$$HL2 = (HL1)\ \varepsilon_w - HLW\ . \tag{45}$$

The longwave radiation is absorbed at the water surface and is not routed through the water.

4.2.4 Evaporative Heat Flux (HE)

A Dalton-type equation is used to compute HE, the evaporative heat flux:

$$HE = -D\ L\ E \tag{46}$$

where:
- D is the density of water (D = 1 g cm^{-3})
- L is the latent heat of vaporization of water
- E is the evaporation rate of the water (cm s^{-1}).

The latent heat of vaporization is computed by

$$L = 595 - 0.56\ T_w \tag{47}$$

where T_w is the water temperature (°C) as in Equation (44). The evaporative rate is assumed to be a function of windspeed and the vapor pressure gradient, ($e_w - e_a$), immediately above the water surface:

$$E = (\ e_w - e_a\ )\ f(u) \tag{48}$$

where e_w is the saturation vapor pressure (mb) at the water's surface (Equation (65)), e_a is the atmospheric vapor pressure (Equation (66)), and f(u) is the designated wind function (u being wind speed) recommended by Ryan and Harleman (1976) and Brocard and Harleman (1976):

$$f(u) = 1.3 \times 10^{-7}\, u + 1.1 \times 10^{-7}\, TVDIFF^{1/3} \quad . \tag{49}$$

TVDIFF is the difference in virtual temperatures (°C) of the ambient air and the saturated air at the water's surface. The virtual temperature of a parcel of moist air is the temperature that the air would be if it were dry but maintained at the same density and total pressure as the moist air. The virtual temperature of air above the stream (the ambient air), TVA, and the air at the water's surface (the saturated air), TVW, is given by

$$TVA = \frac{P}{P - 0.378\, e_a} \tag{50}$$

and

$$TVW = \frac{P}{P - 0.378\, e_w} \quad . \tag{51}$$

The variable P is the total atmospheric pressure (mb) given by

$$P = 1000\, RP \tag{52}$$

where RP is given by Equation (4). TVDIFF (°C) is then

$$TVDIFF = TVA - TVW \quad . \tag{53}$$

The virtual temperature difference (TVDIFF) becomes important when the water temperature is relatively high or the wind speed relatively low. In such situations, free convection can occur. For small streams, water temperatures in excess of 25°C (Brown, 1971) have been reported. At these elevated temperatures the rate of cooling increases and the virtual temperature difference term becomes necessary to simulate observed evaporation rates.

4.2.5 Convective Heat Flux (HC)

The convective heat flux at the air-water interface is calculated using a Bowen ratio approach (Bowen 1926; Raphael 1962). The Bowen ratio, RB, is

$$RB = \frac{HC}{HE} = 0.61 \left(\frac{T_w - T_a}{e_w - e_a} \right) \quad . \tag{54}$$

Thus,

$$HC = RB \bullet HE \quad . \tag{55}$$

4.2.6 Advected Energy (HADV)

A mass balance mixing equation is used to calculate the energy advected into the stream by the inflow of groundwater:

$$HADV = \frac{QE \bullet TE + QGW \bullet TGW}{QE + QGW} - TE \tag{56}$$

where QE is the stream flow at the beginning of the sub-section ($\ell\ s^{-1}$), QGW is the total inflow from groundwater seepage through the sub-section ($\ell\ s^{-1}$), and TE and TGW are the respective temperatures (°C) for QE and QGW.

4.2.7 Net Temperature Change (ΔT)

The change in temperature (ΔT) in a given time period for a specific sub-section is calculated by

$$\Delta T = \left(\frac{HS + HB + HL2 + HE + HC}{QE + \frac{QGW}{2}} \right) SA \bullet K + HADV \quad . \tag{57}$$

The variables HS (Equation (31)), HL2 (Equation (45)), HE (Equation (46)), and HC (Equation (55)) are the appropriate calculated energy budget components in ly s^{-1} for the specified time period. HB represents 1/32 of the total amount of energy stored by the bed (Equation (32)) that is now being released back to the water in uniform amounts over an eight hour period. HADV (Equation (56)) is the energy advected into the stream by groundwater seepage (°C). QE and QGW are the streamflow at the beginning of the

sub-section ($\ell\ s^{-1}$) and the sub-section's total groundwater seepage ($\ell\ s^{-1}$). SA is the sub-section's surface area (SA = LENGTH * WIDTH, m^2). The constant K converts to degrees Celcius (K = 10 cm^2 °C ℓ cal^{-1} m^{-2}).

The predicted change in temperature, when combined with the temperature of water entering the upstream end of the sub-section (TE) results in an estimated outlet temperature (TO) from the stream sub-section:

$$TO = TE + \Delta T \quad . \tag{58}$$

This outlet temperature then becomes the temperature for water entering the next downstream sub-section.

4.3 Forest Shading

When forest shading exists alongside the stream channel, the direct solar, diffuse solar, and atmospheric longwave radiation available above the canopy is attenuated to account for the shading effects of the canopy. In effect, these radiation components are routed through the forest canopy with the amount of radiation being reduced to reflect the interception (shading) by the canopy.

The forest canopy is viewed as one of two types: (1) a "continuous" forest, or (2) a leave or "buffer" strip. In a continuous forest, the natural forest vegetation extends to a sufficient distance perpendicular to the channel to represent a continuous canopy extending away from the stream channel. That is, the width of the forest canopy perpendicular to the stream channel is "infinite". In a buffer strip, the width of the forest canopy perpendicular to the stream channel is, relatively speaking, small. For the TEMP-84 MODEL a rule of thumb is: if the width of the forest canopy extending away from the stream axis is well defined and easily distinguishable and measurable, then the canopy should be considered a buffer strip; otherwise, the canopy represents continuous forest. Buffer strips are assumed to parallel the stream axis.

The shading effects of the canopy are determined as a function of the canopy density (canopy cover coefficient) and the distance the radiant energy must travel to traverse the canopy. For diffuse solar and atmospheric longwave radiation, the radiation is assumed to originate from a point source perpendicular to the stream channel at an angle equal to the average of the forest and hillslope angles. Referring to Figures 14a and 14b, the angle HS is the hillslope angle, B is the perpendicular forest shade angle, and ALT = (HS + B)/2. For direct solar radiation, the radiation source is, of course, the sun. Again, in Figures 14a

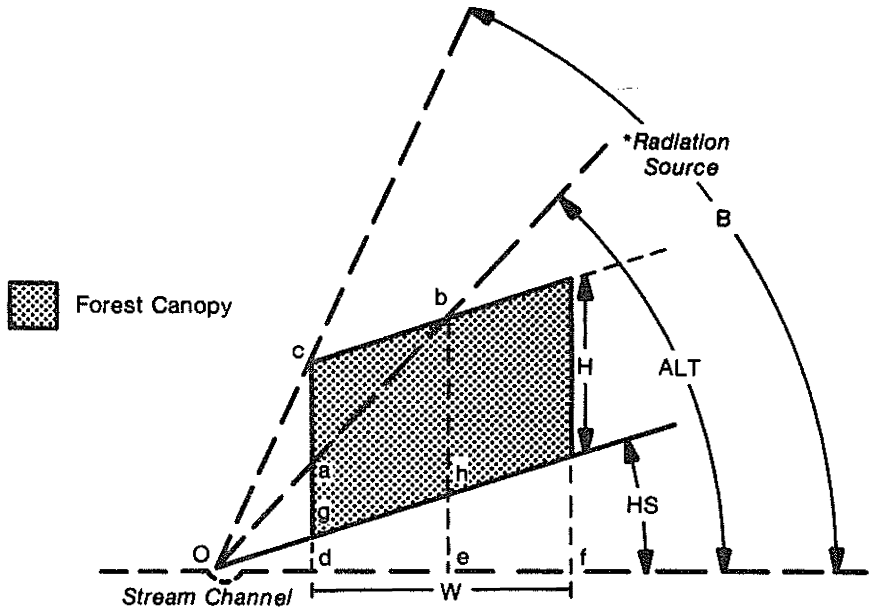


Figure 14a. Canopy path lengths for de $\leq$ w. In this case PL1 = ab/H and PL2 = ob/H. The shaded area represents a leave or buffer strip of width w (m) and tree height H (m).

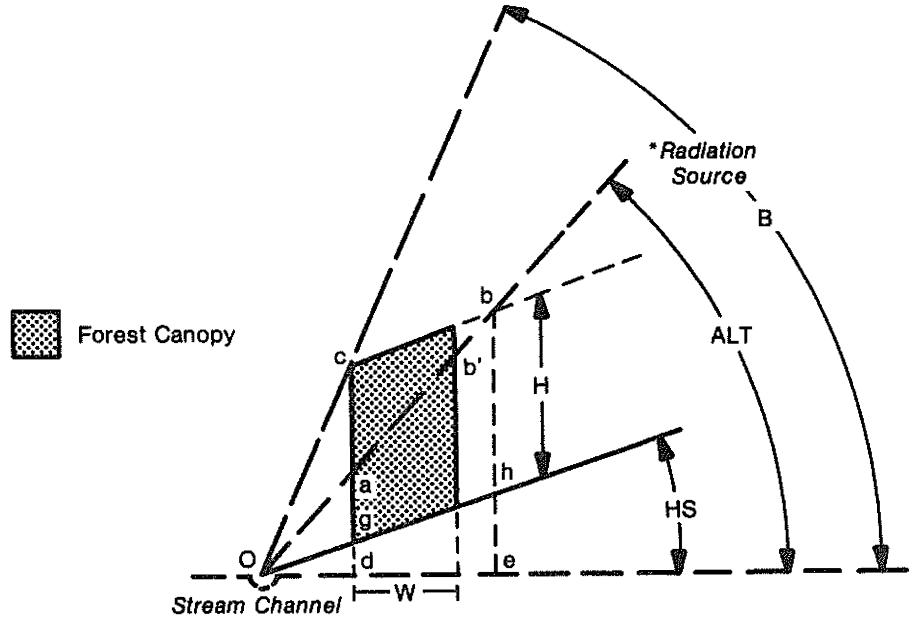


Figure 14b. Canopy path lengths for de > w. In this case PL1 = ab'/H and PL2 = ob'/H . The shaded area represents a leave or buffer strip of width w (m) and tree height H (m).

and 14b, the angle HS is as above, the angle B is the forest shade angle to the southeast, south, or southwest depending on the solar azimuth, and ALT is the solar altitude.

The distance the radiant energy must travel to traverse the canopy is referred to as the path length and is calculated in multiples of the tree height H. When the sun is directly overhead (ALT = 90°) shining directly downward through the canopy, the path length is one. As ALT decreases, the path length increases.

The calculated path length is actually an average path length given by:

$$AVEPL = \frac{PL1 + PL2}{2} \tag{59}$$

where PL1 is the distance from where the radiant energy enters the canopy to where it exits the canopy, and PL2 is the distance from where the radiant energy enters the canopy to the center of the stream channel (Figures 14a and 14b). In Figure 14a, PL1 = ab/H and PL2 = ob/H = PL1 + oa/H. In Figure 14b, PL1 = ab'/H and PL2 = ob'/H = PL1 + oa/H. For direct beam radiation, the average path length (AVEPL) is adjusted to account for the increased distance the radiation must travel through the forest canopy when the incoming direct beam is not perpendicular to the stream axis (Figure 15).

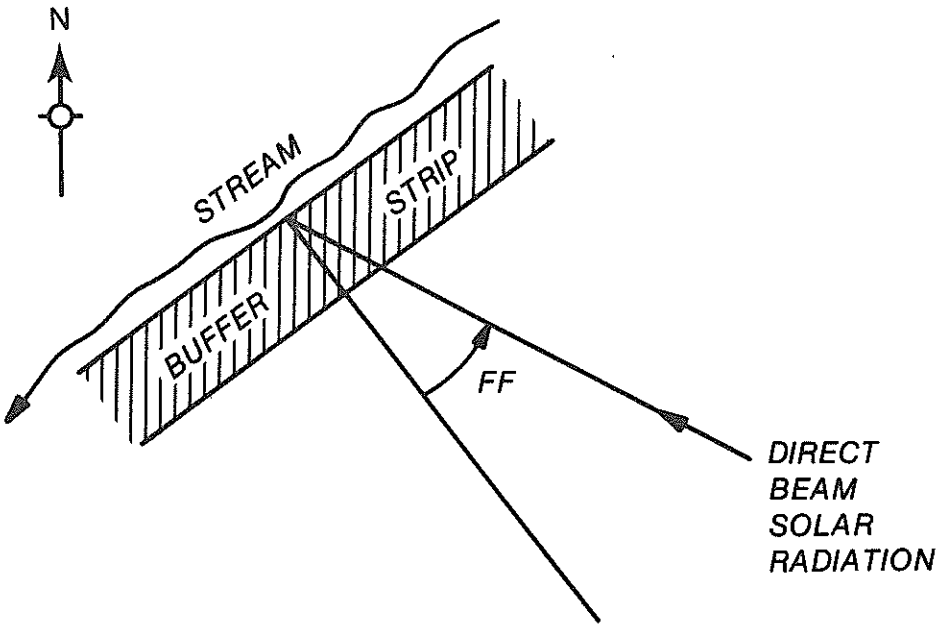


Figure 15. Path length adjustment for direct beam solar radiation when the axis of the buffer strip is not oriented perpendicular to the incoming direct beam radiation.

The calculations performed to compute PL1 and PL2 are:

$$oa = \left(\frac{1}{\cos ALT}\right)\left(\frac{H}{\tan B - \tan HS}\right)$$

$$ab = \left(\frac{H}{\tan B - \tan HS}\right)(\tan B - \tan ALT)\left(\frac{\cos HS}{\sin (ALT - HS)}\right)$$

$$de = ab \cos ALT$$

$$PL1 = \frac{ab}{H} \qquad \text{for } de \leq w < \infty \text{ or } w = \infty$$

$$PL1 = \frac{ab'}{H} = \frac{w}{H \cos ALT} \qquad \text{for } de > w \tag{60}$$

$$PL2 = PL1 + \frac{oa}{H} \tag{61}$$

where H is average tree height (m), w is buffer strip width (m), and the angles HS, B, and ALT are as described above.

If the radiation being routed is diffuse solar or atomspheric longwave then AVEPL is given by Equation (59). If direct solar radiation is being routed

$$AVEPL = \left(\frac{PL1 + PL2}{2}\right)\left(\frac{1}{\cos FF}\right) \tag{62}$$

where FF is the principal angle between the sun and a perpendicular to the stream (Figure 15).

Once AVEPL has been determined, the radiation attenuation function R is given by

$$R = (1 - 0.9\ CC)^{AVEPL}$$

where CC is the canopy cover coefficient ($0 \leq CC \leq 1$).

The average tree height (H), buffer strip width (w), and canopy coefficient (CC) may be varied to simulate different management plans.

4.4 Mass Balance Mixing Equation

When the inflow of a stream section is the result of the confluence of two or three tributaries (three is the maximum allowed by the model), a mass balance mixing equation

is used to calculate the resultant temperature T (°C):

$$T = \frac{\sum_i T_i Q_i}{\sum_i Q_i} \tag{63}$$

where T_i and Q_i represent the water temperature (°C) and flow ($\ell\ s^{-1}$) of tributary i, respectively.

4.5 Air Temperatures Approximated By a Sine Function

Air temperatures may be approximated from the daily minimum and maximum air temperature by means of a sine function:

$$T = \left(\frac{MAX - MIN}{2} \right) \sin (\omega t - 150) + \frac{MAX + MIN}{2} \tag{64}$$

where:

T	is the estimated air temperature (°C)
MAX	are the maximum and minimum daily air temperatures (°C)
MIN	occurring at 1600 hours and 0400 hours local standard time, respectively
ω	is the angular rotation of the earth (ω=15° hr^{-1})
t	is the local standard time in hours past midnight.

4.6 Vapor Pressures

For various calculations the model requires the vapor pressure of the atmosphere and the saturation vapor pressure of the atmosphere and at the water's surface. Saturation vapor pressures (e_s) are calculated using a modified Tabata equation (see Appendix D):

$$e_s = 1.01725 \ \exp \left[21.381 - \frac{5347.5}{T} \right] \tag{65}$$

where T is the temperature of the air (°K) when calculating the saturation vapor pressure of the air, or T is the water temperature (°K) when calculating the saturation vapor pressure at the water surface.

The atmospheric vapor pressure is calculated by

$$e_a = \frac{HUMID}{100} e_s \tag{66}$$

where e_s is given by Equation (65) when T is the midday (1300 hours local standard time) air temperature and HUMID is the midday relative humidity (%). Again, it is assumed that the atmospheric vapor pressure is constant throughout the day until the air temperature drops to the point of saturation. Any additional drop in temperature would create a negative vapor pressure gradient and condensation would occur. The temperature at which saturation is assumed to occur, TSAT (°K), is

$$TSAT = \frac{5347.5}{21.382 - \log_e \left(\frac{e_a}{1.01725} \right)} \quad . \tag{67}$$

If the temperature of the air (T_a) drops below TSAT, the vapor pressure of the air is assumed to be the saturation vapor pressure (e_s) at T_a. That is, if T_a < TSAT then

$$e_a = 1.01725 \exp \left[21.382 - \frac{5347.5}{T_a} \right] \quad . \tag{68}$$

4.7 Solar Parameters

Solar declination. The solar declination (δ) is assumed to remain constant throughout the sunshine duration of a day. The declination for a given day is approximated by

$$\delta = 23.45 \cos \left(\frac{360}{365} (n - 172) \right) \tag{69}$$

where n is the number of days since January 1 (leap years are ignored).

Solar altitude. The solar altitude (ALT) is computed for a given time by

$$ALT = \sin^{-1} (\cos \Theta \cos \delta \cos \omega t + \sin \Theta \sin \delta) \tag{70}$$

where:
- Θ is the latitude of the given site in degrees
- ω is the angular rotation of the earth
- t is local mean solar time in hours less 12.

Solar azimuth. The solar azimuth, AZ (in degrees clockwise from south), for a given time is

$$AZ = \sin^{-1} \left(\frac{\cos \delta \sin \omega t}{\cos ALT} \right) \tag{71}$$

where δ, ω, t, and ALT are as in Equation (70).

Zenith angle. The zenith angle (Z) is the angle between the sun and a vector normal to a horizontal surface. By definition

$$Z = 90 - ALT \quad . \tag{72}$$

The apparent zenith angle (Z') is the angle between the sun and a vector normal to, in this application, the stream surface. It is given by

$$Z' = \cos^{-1} [\sin ALT \cos G + \cos ALT \sin G \cos (STAZ - AZ)] \tag{73}$$

where ALT and AZ are the solar altitude and azimuth as calculated above, G is the slope of the stream in degrees, and STAZ is the aspect of the stream in degrees clockwise from south.

5.0 DATA SENSITIVITIES

When applying a computer model such as TEMP-84, it is desirable to know how errors in input parameters change the model's outputs. Both the magnitude and direction of the changes are useful information. If large errors in an input parameter result in only small changes in calculated outputs then little time and effort should be spent collecting data for that parameter. If you can establish a range for each input parameter, then knowing how an increase and decrease in the value of the parameter changes the outputs enables you to create a data set for the model that will give you an upper or lower bound for the outputs.

This section presents a series of equations that will help you, the user, analyze the data sensitivities of the TEMP-84 MODEL for your particular application. These equations will enable you to determine the direction in change of calculated output temperatures given the direction of change in the input parameter. In some situations the magnitude of the change can be readily calculated. At other times, the magnitude of the change depends upon an estimate of the net energy flux. In these situations the

magnitude of the change in calculated output temperatures can be approximated by first creating a data set utilizing estimates of the input parameters and executing the model providing this data set as input. (These parameter estimates may require a preliminary survey of the stream system.) The resultant outputs then can be used along with the equations to identify "important" data and your data collection resources can be allocated accordingly. A comprehensive survey of the stream system can then be performed.

As you will notice, not all of the input parameters are represented in the equations. Some are omitted because the parameter is easily obtained within an accuracy that would generate an insignificant change in output temperatures. Longitude and latitude of the site are examples of such parameters. Others are omitted because they affect only those components of the model that are less significant in simulating maximum stream temperatures resulting from harvest activities. For these parameters an educated estimate of the parameter's value will suffice. Average windspeed at the stream surface is such a parameter. Average windspeed is an important component in calculating the evaporative and convective heat fluxes and the evaporative and convective fluxes are an important consideration in the simulation process. However, at times when the increase in stream temperatures is high, the direct beam flux is dominant and comparitively, the evaporative and convective fluxes are insignificant.

It should be noted that a linearization method was used to derive some equations that represent approximations (i.e., a $\approx$ instead of a =). This results in good estimates if the magnitudes of the terms representing changes in input parameters are "small". As the magnitudes of these terms increase, the reliability of the resultant approximation may decrease.

5.1 ΔTO - The Change in Output Temperature

Throughout the following discussion, the symbol Δ (delta) represents the change (or error) in the associated value. For example, if T represents temperature then ΔT represents the change in temperature.

As you recall, the equations presented in Section 4 are used to determine the energy flux and net heat gain for each individual stream sub-section. The data sensitivity equations that follow have been modified for simplification to represent an "average" for the stream section. Be aware that as the number of sub-sections increases, the accuracy of the following approximations may decrease.

To begin, let's define H to be the average net energy flux received by the stream section:

$$H = HS + HB + HL2 + HE + HC \tag{74}$$

where HS, HB, HL2, HE, and HC are the stream sections average net solar, heat conducted to bedrock, net longwave, evaporative, and convective fluxes, respectively. The value of H is reported by the model in the table of water temperatures (Figure 8). Further, let's define Q to be the average flow through the section:

$$Q = QE + \tfrac{1}{2}QGW \ . \tag{75}$$

QE is the streamflow at the beginning of the section:

$$QE = \sum_i Q_i \tag{76}$$

where Q_i is the flow of tributary i. QGW is the total groundwater seepage through the stream section:

$$QGW = (Q_{gw})\left(\frac{L}{100}\right) \tag{77}$$

where Q_{gw} is the input groundwater seepage per 100 m of channel and L is the stream section length. The value of Q is reported by the model as average Q (Figure 7). Referring to Equations (57) and (58), the water temperature at the stream section outlet, TO, is

$$TO = TE + \frac{H\,SA}{Q}\,n\,k + HADV \tag{78}$$

where:
- TE is the water temperature at the beginning of the stream section
- SA is the surface area of each sub-section
- n is the number of sub-sections the stream section was divided into
- k = 10 cm^2 °C ℓ cal^{-1} m^{-2}
- HADV is the energy advected into the stream section by groundwater seepage.

The change in TO can be approximated by

$$\Delta TO \approx \Delta TE + \left(\frac{H\,SA}{Q}\,k\right)(n + \Delta n)\left(\frac{Q}{Q + \Delta Q}\right)\left(\frac{\Delta H}{H} + \frac{\Delta SA}{SA}\right) + \Delta HADV \ . \tag{79}$$

The significance of errors in TE and HADV are obvious. The effects of errors in n, H, Q, and SA are relative to their initial values. The smaller the term $\frac{H\,SA}{Q}$ the more

acceptable are larger errors in H, Q, and SA. Generally, $H < .03$ ly s^{-1} so that a worst case can be determined by assuming $H = .03$ ly s^{-1}. Note that a positive change (an increase) in TE, n, H, SA, and HADV results in a positive change in TO while a positive change in Q results in a negative change (a decrease) in TO. Each of these components is affected by one or more input parameters.

5.2 ΔTE - The Change in Inflow Temperature

TE is computed by Equation (63). The effects of errors in the input inflow and water temperature of each tributary can be approximated by

$$\Delta TE \approx \frac{\sum_i (T_i \Delta Q_i + \Delta T_i Q_i + \Delta T_i \Delta Q_i)}{\sum_i (Q_i + \Delta Q_i)} \quad . \tag{80}$$

T_i and Q_i are the input water temperature and flow of tributary i, respectively.

5.3 ΔQ - The Change in Inflow

From Equations (75), (76), and (77):

$$\Delta Q = \Delta QE + \tfrac{1}{2}\Delta QGW \tag{81}$$

where:

$$\Delta QE = \sum_i \Delta Q_i \tag{82}$$

and

$$\Delta QGW = (\Delta Q_{gw})(\frac{L}{100}) + (Q_{gw})(\frac{\Delta L}{100}) + (\Delta Q_{gw})(\frac{\Delta L}{100}) \quad . \tag{83}$$

5.4 Δn - The Change in the Number of Sub-sections

The number of sub-sections within the stream section is

$$n = \text{INTEGER}\ \left[\frac{\frac{L}{v} + 840}{900}\right] \tag{84}$$

where L is the input section length and v is the input water velocity through the section. Thus,

$$n + \Delta n = \text{INTEGER}\ \left[\frac{\frac{L + \Delta L}{v + \Delta v} + 840}{900}\right] . \tag{85}$$

5.5 ΔSA - The Change in Surface Area

The surface area of each sub-section is given by

$$SA = L' w \tag{86}$$

where L' is the sub-section length

$$L' = \frac{L}{n} \tag{87}$$

and w is the input stream section width. Thus,

$$\frac{\Delta SA}{SA} = \frac{\Delta L'}{L'} + \frac{\Delta w}{w} + \frac{\Delta L'}{L'}\,\frac{\Delta w}{w} \tag{88}$$

where

$$\frac{\Delta L'}{L'} = \left(\frac{n}{n + \Delta n}\right)\left(\frac{L + \Delta L}{L}\right) - 1 . \tag{89}$$

5.6 ΔHADV - The Change in Advected Energy

HADV is computed by Equation (56). The effects of errors in the calculated section inflow, section inflow temperature, groundwater seepage, and the input groundwater temperature can be approximated by

$$\Delta HADV \approx HADV\left(\frac{QE}{QE + QGW}\,\frac{\Delta QGW}{QGW} - \frac{\Delta QE}{QE + QGW} + \frac{\Delta TGW - \Delta TE}{TGW - TE}\right) \tag{90}$$

where TGW is the temperature of the groundwater seepage. Remember, HADV is non-zero only when the groundwater seepage is positive.

If we assume that $\Delta H = 0$ then the above equations can be used to determine the combined effects that errors in the input parameters T_i, Q_i, TGW, Q_{gw}, L, v, and w have on TO.

5.7 ΔH - The Change in Net Energy Flux

From Equation (74),

$$\Delta H = \Delta HS + \Delta HB + \Delta HL2 + \Delta HE + \Delta HC \quad .$$

The determination of ΔHS, ΔHB, ΔHL2, ΔHE, and ΔHC would be complex and an attempt to simplify their estimation would result in poor approximations. (If they could be easily determined or closely approximated then there would be no need for the model.) In this discussion we will assume that H is equal to DIRHS4, the direct beam component of the solar flux that enters the water (Equation (20)), for these reasons. If you are analyzing the data sensitivities for a specific application of TEMP-84 then your interest should be in the associated errors when the solar radiation flux term HS + HB is dominant. That is, if your proposed harvest activities will not significantly increase the solar flux available to the stream, then the resultant stream temperature changes are small and the errors in input parameters are of little consequence. The effect of HB is simply to reduce the maximum value of HS (see Equations (31) and (32)). Ignoring the HB term establishes a maximum for HS. When the solar flux term is dominant, the contribution of the diffuse component is small and can be ignored.

Even with these assumptions, an attempt to estimate $\Delta H = \Delta DIRHS4$ is impractical because of the interactions of the inputs required to calculate the average path length in Equation (9). Therefore, this discussion will focus on the input parameters used to compute DIRHS4, and how values for these parameters can be chosen so that a minimum and maximum value of DIRHS4 is calculated by the model. This information along with the above equations can be used to create a data set for the TEMP-84 MODEL that should result in the simulation of near minimum and near maximum values of the output temperatures. These values will then serve to bound the output temperatures that were simulated using the "best estimates" of each input parameter. Of interest are the input parameters that are used in the calculations in Equations (2), (9), (10), (16), and (20).

5.7.1 Equation (2) - The Direct Beam Flux Above The Canopy

In Equation (2), the direct beam solar flux available above the forest canopy is determined as a function of mean site elevation and stream aspect and gradient. In nearly all cases, mean site elevation should be an acceptable approximation for each stream section's elevation. It can be shown that if elevation is 1500 m $\pm$ 500 m then the error in the computed direct beam flux is less than 4% when the solar altitude is greater than 20°. Stream aspect and gradient are easily obtained within an accuracy that would generate insignificant errors in the calculated direct beam flux. The direct beam flux available above the canopy is maximized by selecting a maximum value for elevation and choosing the stream aspect and gradient so that the plane of the stream section is tilted towards the sun at those times the sun is at its highest altitude and shining directly on the stream. Selecting a minimum elevation value and the stream aspect and gradient so that the plane of the stream section faces more away from the sun will result in a minimum value of the direct beam component being calculated.

5.7.2 Equations (9) and (10) - The Direct Beam Flux Below The Canopy

The amount of direct beam flux available below the forest canopy is calculated in Equation (9) or (10). The most important consideration for these equations is the position of the sun relative to the topographic and forest shade angles and the stream section.

Topographic shading. If the solar altitude is less than the topographic shade angle then the direct beam flux is zero. Decreasing the topographic shade angle increases the time sunshine is available to the stream which potentially causes an overall increase in calculated stream temperatures. Increasing the topographic shade angle decreases the duration of sunshine which potentially decreases the calculated stream temperatures.

Canopy opening. When the solar altitude is greater than the forest shade angle then the sun shines directly onto the stream through the canopy opening above the channel. It is at these times that the stream experiences maximum heat gain. To maximize the direct beam flux available to the stream, increase the time the sun is above the canopy by selecting a minimum forest shade angle. To minimize the direct beam flux available to the stream, decrease the time the sun is above the canopy by selecting a maximum forest shade angle.

Referring to Figure 15, as the sun moves from being perpendicular to the axis of the stream, the path length increases (assuming a constant solar altitude). Stream aspect is

most critical when the solar altitude is less than the forest shade angle and the sun nearly parallels the stream axis. The sun may actually be shining on the stream through the canopy opening above the channel but the model may be routing the solar radiation through the forest canopy. If this situation occurs when solar altitudes are low then the error can probably be ignored. However, if the solar altitude is high the error could be significant. At these times you can maximize the direct beam flux by choosing the stream aspect to align with the solar azimuth.

Canopy cover coefficient. The direct beam flux is routed through the forest canopy when the solar altitude is greater than the topographic shade angle but less than the forest shade angle. The amount of direct beam flux available below the forest canopy is determined by Equation (9) using the canopy cover coefficient and the calculated path length of the direct beam radiation through the forest canopy. Selecting a minimum value for the forest canopy cover coefficient results in a maximum amount of direct beam flux available below the canopy. A maximum value for the coefficient results in a minimum amount of direct beam flux available below the canopy.

Path length. The path length of the direct beam flux is a function of the input parameters stream aspect, average tree height, buffer strip width, hillslope angle, and forest shade angle. To maximize the amount of direct beam flux available below the canopy, the calculated path length should be minimized. The path length is at a minimum when the hillslope angle is at a minimum and, if the stream adjacent forest is a buffer strip, when the tree height is at a maximum and the buffer width is at a minimum. If the forest is continuous then the tree height has no bearing on the calculations and there is no buffer width. Under certain conditions the selection of a minimum forest shade angle results in a minimum path length while other conditions require the selection of a maximum forest shade angle to minimize the path length. The shading angle you should select is dependent upon the range of solar altitudes you are interested in. In general the following rules apply. If the stream adjacent forest is continuous and you are interested in those times of day when the solar altitude is such that

$$3 \tan ALT < 2 \tan B + \tan HS \qquad (91)$$

where: ALT is the solar altitude
B is the forest shade angle
HS is the hillslope angle

then a minimum forest shade angle results in a minimized path length. If the stream adjacent forest is continuous and you are interested in those times of day when the solar altitude is such that

$$3 \tan ALT > 2 \tan B + \tan HS \tag{92}$$

then a maximum forest shade angle results in a minimized path length. If the stream adjacent forest is a buffer strip then first determine the angle f given by

$$\tan f = \frac{h \tan B + w \tan HS (\tan B - \tan HS)}{h + w (\tan B - \tan HS)} \tag{93}$$

where h is the average tree height and w is the buffer width. Now, if ALT < f then a maximum forest shade angle results in a minimum path length. If ALT > f then the value of the forest shade angle should be selected as for a continuous forest. Note that if you select a maximum value for the forest shade angle you must consider the effects of shortening the duration of time the sun is shining directly on the stream from above the forest shading.

To minimize the amount of direct beam flux available below the forest canopy, the calculated path length should be maximized. The path length is at a maximum when the hillslope angle is at a maximum and, if the stream adjacent forest is a buffer strip, when tree height is at a minimum and the buffer width is at a maximum. If the stream adjacent forest is continuous and you are interested in those times of day when the solar altitude satisfies Equation (91) then a maximum forest shade angle results in a maximum path length. If the stream adjacent forest is continuous and you are interested in those times of day when the solar altitude satisfies Equation (92) then a minimum forest shade angle results in a maximum path length. If the stream adjacent forest is a buffer strip then determine the angle f given by Equation (93). If ALT < f then a minimum forest shade angle results in a maximum path length. If ALT > f then the value of the forest shade angle should be selected as for a continuous forest. If you select a minimum value for the forest shade angle you must consider the effects of lengthening the duration of time the sun is shining directly on the stream from above the forest shading.

5.7.3 Equation (16) - The Direct Beam Flux At The Water Surface

The shading effects of brush and logs overhanging the water surface are calculated in Equation (16). Assuming the calculation of DIRHS2 by Equations (9) and (10) is exact, the

error in the amount of direct beam flux reaching the stream surface is

$$\Delta DIRHS3 = - \Delta BRUSH \bullet DIRHS2 \qquad (94)$$

where BRUSH is the proportion of the water surface shaded by overhanging brush and logs. To maximize the direct beam flux reaching the water surface, select a minimum value for BRUSH. To minimize the direct beam flux reaching the water surface, select a maximum value for BRUSH.

5.7.4 Equation (20) - The Direct Beam Flux Entering The Water

In Equation (20), the flux of direct beam radiation entering the water is calculated as a function of the albedo of moving water (REFL). Assuming the calculation of DIRHS3 by Equation (16) is exact, the relative error in the amount of direct beam flux entering the water is

$$\frac{\Delta DIRHS4}{DIRHS4} = - \frac{\Delta REFL}{1 - REFL} \cdot \qquad (95)$$

REFL is calculated by Equations (18) and (19) as a function of Z', the apparent zenith angle. When the error in Z' is as much as 5°, the error in DIRHS4 given by Equation (95) is less than 1% if $Z' \leq 40°$, less than 5% if $Z' \leq 65°$, and less than 10% if $Z' \leq 70°$. The error is large if $Z' > 75°$ but at these times the amount of direct beam flux is small (Equation (2)), and the errors are generally insignificant. The input parameters stream aspect and gradient determine Z' and are easily obtained within an accuracy that would generate less than a 5° error in Z'. Thus, in most cases the computations of Equation (20) can be assumed to be exact.

6.0 EPILOGUE

At this time the model has not been formally validated. Until it is, it is recommended that you exercise caution in its use. Avoid modeling long or complex stream systems. Reduce the propogation of errors as much as you can by supplying measured inflow temperatures for each stream section when possible. Have an understanding of the modeling assumptions and processes before you collect the input data and give them consideration while you collect the data. Bound your best estimate of each parameter and use the information presented in Section 5.0 to create bounds for the simulated temperatures.

It is entirely your responsibility to evaluate the modeling assumptions and methods presented to determine the feasibility of using TEMP-84 for your specific application.

Questions, suggestions, and comments relating to the model are most welcome and should be directed to the WSDG.

REFERENCES

Austin, R. W., and G. Halikas. 1976. The index of refraction of seawater. Scripps Instit. Oceanogr., San Diego, CA., Tech. Report SIO 76-1. 121 pp.

Bowen, I. S. 1926. The ratio of heat losses by convection and evaporation from any water surface. Physical Review. Series 2, Vol. 27:779-787.

Brocard, D. N., and D. R. F. Harleman. 1976. One dimensional temperature prediction in unsteady flow. J. Hydraul. Div., A.S.C.E., 102(HY3):227-239.

Brooks, F. A. 1959. An introduction to physical microclimatology. Univ. Calif., Davis. 264 pp.

Brown, G. W. 1969. Predicting temperatures of small streams. Water Resour. Res. 5(1):68-75.

Campbell, Gaylon S. 1977. An introduction to environmental biophysics. Springer-Verlag, Inc., New York. 159 pp.

Crittenden, R. N. 1978. Sensitivity analysis of a theoretical energy balance model for water temperature in small streams. Ecological Modeling 5:207-224.

Davis, Richard A. 1977. Principles of oceanography. Addison-Wesley Publishing Co., Menlo Park, CA. 505 pp.

Jerlov, W. G. 1976. Marine optics. Elsevier Scient. Publ. Comp., Elsevier Oceanography Series, 14. 231 pp.

Kondratyev, K. Ya. 1972. Chapter II: Radiation characteristics of the underlying surface. pp. 17-48. In: Radiation Processes in the Atmosphere, World Meteorological Organization, WMO-No. 309.

Lee, Richard. 1978. Forest microclimatology. Columbia University Press, New York. 276 pp.

List, Robert J. 1966. Smithsonian meteorological tables. Smithsonian Institute, Washington, D.C. 527 pp.

Liu, Benjamin Y. H., and Richard C. Jordan. 1960. The interrelationship and characteristic distribution of direct, diffuse and total solar radiation. Solar Energy 4(3):1-19.

Ponce, S. L., H. Boyne, W. D. Striffler, and E. Ellis. 1981. A temperature model for small upland streams. Completion Report, USDA Forest Service, RMFRES. 102 pp.

Raphael, J. M. 1962. Prediction of temperature in rivers and reservoirs. J. Power Div., A.S.C.E. 88(PO2):157-181).

Reifsnyder, William E., and Howard W. Lull. 1965. Radiant Energy in Relation to Forests. USDA Forest Service, Technical Bulletin No. 1344. 111 pp.

Robinson, N. (Ed.). 1966. Solar radiation. Elsevier Pub. CO., New York. 347 pp.

Rosenberg, Norman J. 1974. Microclimate: the biological environment. John Wiley & Sons, New York. 315 pp.

Ryan, P. J., and D. R. F. Harleman. 1976. Transient cooling pond behavior. Hydraul. Eng. and the Environ., Proc. 21st Ann. Hydraul. Div. Speciality Conf., A.S.C.E., Boseman Montana.

Satterlund, Donald R. 1979. An improved equation for estimating longwave radiation from the atmosphere. Water Resour. Res. 15(6):1649-1650.

Sellers, William D. 1965. Physical climatology. University of Chicago Press, Chicago. 272 pp.

Solomon, Rhey M., Peter F. Ffolliott, Malcus B. Baker, Jr., and J. R. Thompson. 1976. Computer simulation of snowmelt. USDA Forest Service Research Paper RM-174. 8 pp.

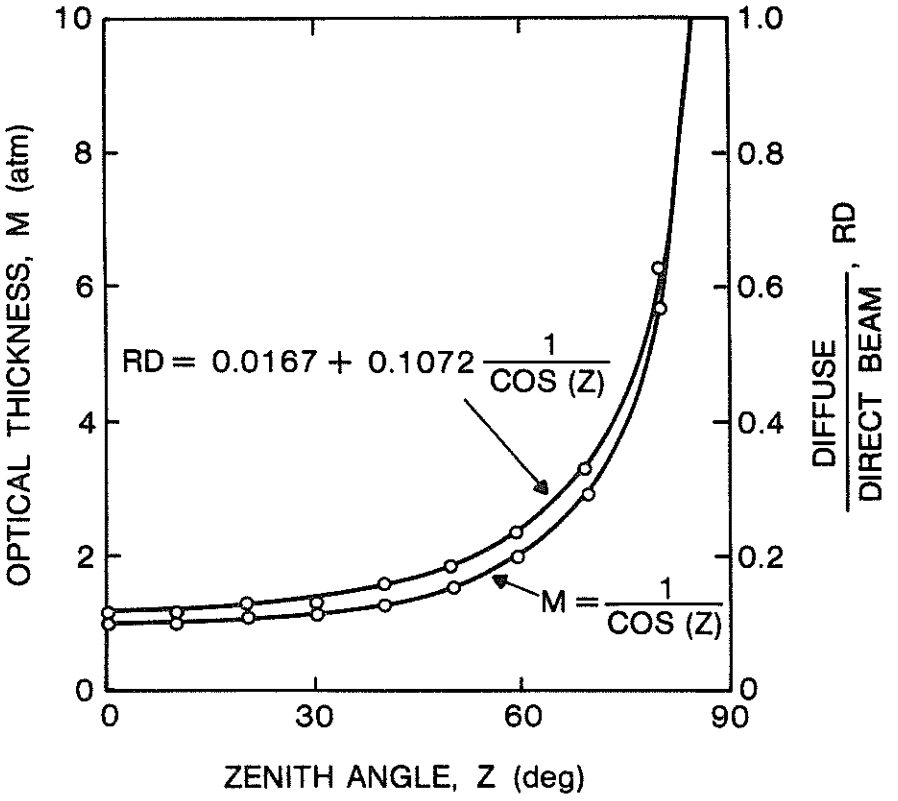
Tennessee Valley Authority, Division of Water Control Planning Engineering Laboratory. 1972. Heat and Mass Transfer Between a Water Surface and the Atmosphere. Water Resources Research Laboratory Report No. 14.

Weast, Robert C., and Samuel M. Selby (Ed.). 1966. Handbook of Chemistry and Physics, 47th Edition. Chemical Rubber Co., Cleveland, Ohio.

Williams, Jerome. 1970. Optical properties of the sea. U.S. Naval Instit., Annapolis, Maryland. 123 pp.

APPENDIX A

Optical Thickness of the Atmosphere and Ratio of Diffuse to Direct Beam Radiation in Relation to the Zenith Angle



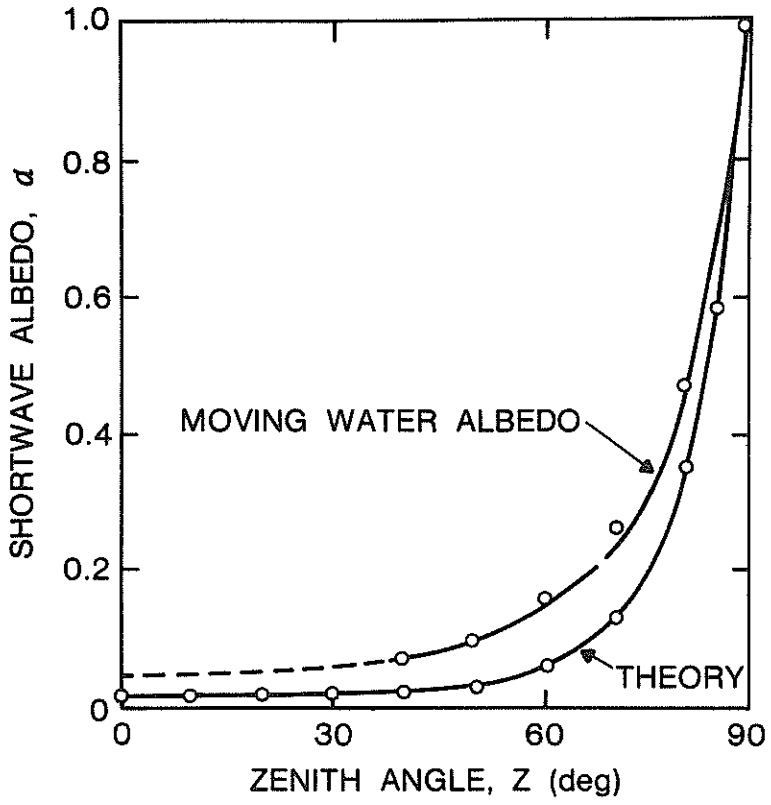
M = Optical thickness of the atmosphere from Robinson (1966).

RD = Ratio of diffuse to direct beam radiation developed from data for "Standard Cloudless Atmosphere" (Brooks, 1959) in Reifsnyder and Lull (1965).

Z = Zenith angle.

APPENDIX B

Relationship Between Shortwave Albedo (α) and Zenith angle (Z)



Moving water albedo; equations developed from data in Sellers (1965):

$$\alpha = \frac{0.091}{\cos Z} - 0.0386 \qquad 0° \leq Z \leq 80°$$

$$\alpha = 0.0515\ Z - 3.635 \qquad 80° < Z \leq 90°$$

Theoretical albedo for a plane water surface (Sellers, 1965; Davis, 1977):

$$\alpha = 50\left(\frac{\sin^2(Z-r)}{\sin^2(Z+r)} + \frac{\tan^2(Z-r)}{\tan^2(Z+r)}\right) \qquad \text{Freshnel's Formula}$$

where: r is the angle of refraction

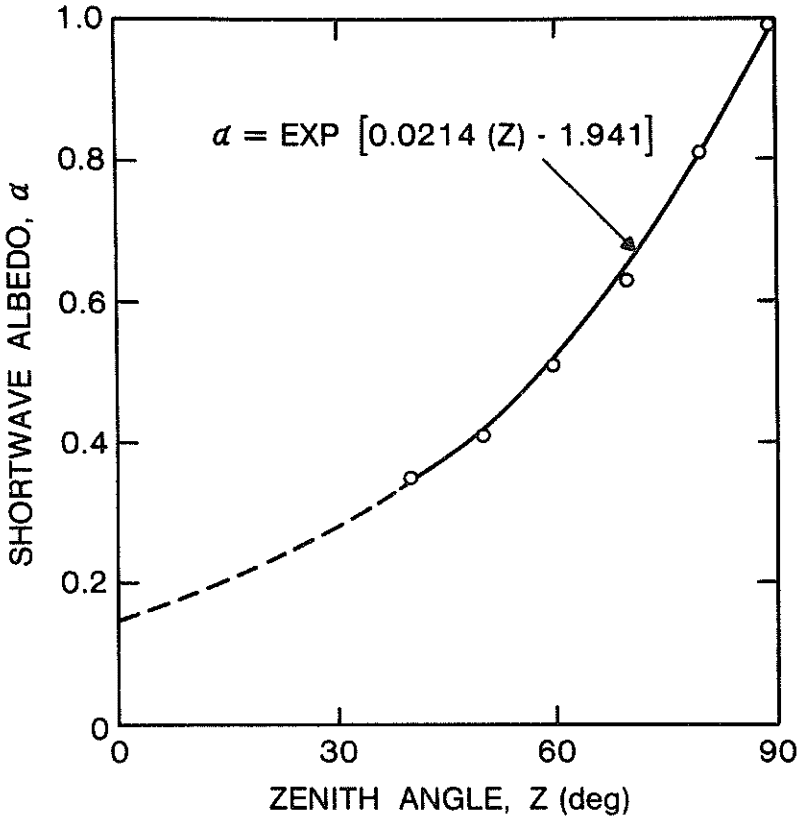
$$= \sin^{-1}\left(\frac{\sin Z}{i}\right) \qquad \text{Snell's Law}$$

i is the index of refraction

= 1.3333 for water at 20° C

APPENDIX C

Relationship Between Shortwave Albedo and Dry Sand Relative to the Zenith Angle (Adopted from Sellers (1965))



α = Shortwave albedo

Z = Zenith angle

APPENDIX D

Saturation Vapor Pressure (e_s) in Relation to Temperature

Temperature		Tabular Values of e_s (mb)		Predicted Values of e_s (mb) from Equations[c]							
°C	°K	e_s[a]	e_s[b]	e_s[d]		e_s[e]		e_s[f]		e_s[g]	
0	273	6.11	6.10	6.35	(3.9)	6.68	(9.3)	6.01	(1.6)	6.12	(0.2)
5	278	8.72	8.72	8.79	(0.8)	9.02	(3.4)	8.55	(2.5)	8.70	(0.2)
10	283	12.27	12.28	12.16	(0.9)	12.17	(0.8)	12.02	(2.0)	12.22	(0.4)
15	288	17.04	17.05	16.83	(1.3)	16.42	(3.7)	16.68	(2.1)	16.97	(0.4)
20	293	23.37	23.38	23.30	(0.3)	22.17	(5.2)	22.90	(2.0)	23.30	(0.3)
25	298	31.67	31.67	32.25	(1.8)	29.91	(5.6)	31.11	(1.8)	31.64	(0.1)
30	303	42.43	42.43	44.63	(5.2)	40.37	(4.9)	41.82	(1.4)	42.55	(0.3)
40	313	73.77	73.76	85.49	(15.9)	73.53	(0.3)	73.50	(0.4)	74.77	(1.4)
Average deviation from tabular values =					3.8%		4.2%		1.7%		0.4%

[a] List (1966)

[b] Weast and Selby (1966)

[c] Values in parenthesis are absolute values of the deviations between tabular and predicted vapor pressures expressed as a percent of the tabular values.

[d] Crittenden (1978): $e_s = 6.35 \exp [0.65\ T]$ where T is in °C.

[e] Rosenburg (1974): $e_s = 10^{(0.02604\ T + 0.82488)}$ where T is in °C.

[f] Tabata (1973) as reported in Lee (1978): $e_s = \exp [21.382 - \frac{5347.5}{T}]$ where T is in °K.

[g] Modified Tabata equation: $e_s = 1.01725 \exp [21.382 - \frac{5347.5}{T}]$ where T is in °K and $273° \leq T \leq 313°$.

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